COMPARATIVE STRENGTH ASSESSMENT OF CANFLEX AND 37-ELEMENT FUEL BUNDLES†

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ABSTRACT

It is important that fuel bundles have adequate mechanical strength to withstand the loads applied to them during various operating conditions. This paper compares the mechanical strengths of CANFLEX® and 37-element fuel bundles that have been subjected to hydraulic drag load.

This paper examines the mechanical strengths of CANFLEX and 37-element fuel bundles under two conditions: normal operating conditions and refuelling conditions. These conditions cause axial compression in the fuel bundles, bending of the fuel elements, and bending of the end plates. The mechanical strength of the bundles was assessed using finite-element calculations. The results provide insights into the load-carrying mechanisms and capabilities of CANDU® fuel bundles.

During normal operating conditions, the last fuel bundle in a fuel channel is supported by the shield-plug; during refuelling conditions, the last fuel bundle in a fuel channel is supported by the side stops. Under these conditions, the total axial loads on the string of the fuel bundles are carried mainly by the fuel elements that contact the support. These conditions generate high stresses in both the end plates and in the fuel elements that contact the support.

The CANFLEX fuel bundle contains 5 more radial ribs in each end-plate than the 37-element fuel bundle. Also, the radial ribs of the CANFLEX fuel bundle are wider than the radial ribs of the 37-element fuel bundle. These two features combine to strengthen the end plates of the CANFLEX bundle in a region that is highly stressed. On the other hand, the outer fuel elements of the CANFLEX fuel bundle have a smaller diameter than the fuel elements of the 37-element fuel bundle. This difference results in somewhat higher stresses in the outer elements of the CANFLEX fuel bundle design compared with the outer elements of the 37-element design. Overall, for the analysed conditions, the 37-element fuel bundle has the highest stress of the two fuel bundles.

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1. INTRODUCTION

A fuel bundle is made up of fuel elements held together by 2 end plates (Figure 1). The end plates consist of concentric rings and radial ribs. The fuel elements are made of Zircaloy tubes that contain UO_2 fuel pellets. The 37-element (Figure 2) and the CANFLEX (Figure 3) fuel bundles have similar designs in many aspects. However, some important design differences between these 2 fuel bundles are relevant to this assessment.

The 37-element fuel bundle contains 37 fuel elements: 1 element at the centre, 6 elements on the inner ring, 12 elements on the intermediate ring, and 18 elements on the outer ring. All fuel elements in the 37-element fuel bundle have the same diameter. Each 37-element end-plate has 11 radial ribs and 3 rings.

The CANFLEX fuel bundle contains 43 fuel elements: 1 element at the centre, 7 elements on the inner ring, 14 elements on the intermediate ring, and 21 elements on the outer ring. Fuel elements on the outer and intermediate rings have a smaller diameter, hence less strength, than the fuel elements located on the inner ring and at the centre of the bundle. Each CANFLEX end-plate has 16 radial ribs and 3 rings. The radial ribs are wider than the radial ribs in the 37-element design; however, the rings are narrower than the rings in the 37-element design.

During normal operating conditions the last fuel bundle in a fuel channel is supported by the shield-plug; during refuelling conditions, the last fuel bundle in a fuel channel is supported by the side stops. Under these conditions the total axial loads on the string of the fuel bundles are carried mainly by the fuel elements that contact the support. These conditions generate high stresses in the end plates and in the fuel elements that contact with the support. Also, the eccentricity of the support and the unsupported fuel elements causes additional bending of the end plates.

The design qualification of the strength of the CANFLEX bundle was done by a combination of out-reactor tests, analytical assessments, and demonstration irradiations. These tests and assessments cover in-reactor loading and support conditions that are expected during normal and refuelling operations in a CANDU 6 reactor. The test results have been reported separately [1, 2, 3], and show that the CANFLEX fuel bundles can withstand the loads of both the normal and the refuelling operations.

The objective of this paper is to present a comparative assessment of the mechanical strength of the CANFLEX and 37-element fuel bundle designs. The focus is to provide additional insights into and information about the mechanical strength and the load-carrying mechanisms and capabilities of the CANFLEX fuel bundle during normal operating and during refuelling conditions. Two end conditions are discussed: shield-plug support and side-stop support.

First, the paper describes the 2 fuel bundle models developed using the ANSYS® finite-element computer code. Second, the validation and verification of these fuel-bundle models are discussed. Finally, the results of this assessment are presented and discussed.

ANSYS® is a registered trade mark of SAS IP, Inc.

2. PREVIOUS WORK

In an earlier study, Manu [4] compared the strength of the highly advanced core (HAC) fuel bundle with the strength of the 37-element fuel bundle under refuelling conditions. First, the ANSYS finite-element computer code was used to identify the load-carrying mechanisms and capabilities of 37-element fuel bundles. Then, these concepts were used to provide the required assessments. The same concepts are used again, in this paper, to assess and to discuss the strength of the CANFLEX fuel bundle compared with the strength of the 37-element fuel bundle.

3. FINITE-ELEMENT MODELLING

Manu [4] originally developed the finite-element models for the 37-element and CANFLEX fuel bundles. In the present study, the 37-element model was modified to update end-plate design changes, and the CANFLEX model was refined so that similar finite-element models are used for these 2 fuel bundles. The finite-element model of the CANFLEX fuel bundle (Figure 2) consists of 1324 finite elements and 1251 nodes; the finite-element model of the 37-element fuel bundle (Figure 3) consists of 1112 finite elements and 1055 nodes. Eight additional finite elements and sixteen additional nodes are used in both models to simulate the side-stop supports during refuelling. To model the eccentric shield-plug support, at the intermediate ring of the CANFLEX fuel bundle, 55 finite elements and 110 nodes are used. Three-dimensional elastic beam finite elements are used to model the fuel sheaths and the end plates. The side-stop and shield-plug supports are also modelled with three-dimensional finite elements by assigning to them a much higher strength than that of the end-plate. The geometrical and material data used for modelling these fuel bundles are obtained from the current design drawings of the CANFLEX and 37-element fuel bundles.

During normal operation, the last fuel bundle in a fuel channel rests on the shield-plug, whereas during refuelling it rests on the side stops. The shield-plug supports the outer and intermediate rings of the end plates and partially supports the outer and intermediate radial ribs of the end plates. In comparison, only a few of the outer fuel elements are supported by the side stops during refuelling (Figure 4). In addition, it should be mentioned that the side stops generate eccentric loading on these fuel elements. The hydraulic load exerts axial compressive force on the bundle. To simulate the shield-plug support condition, the nodes of the finite-element models that contact the shield-plug are prevented from moving in the axial direction of the fuel bundles. To simulate the side-stop support condition, 8 of the outer fuel elements are eccentrically restrained from moving in the axial direction of the fuel bundles. The total hydraulic load exerted on the fuel bundles is assumed to be carried equally among all fuel elements. Hence the total load on the fuel bundles is divided by the number of fuel elements, and the resulting load is applied axially to each fuel element.

Spacer and bearing pads of fuel elements, end-cap-to-end-plate welds, initial bowing of fuel elements, interaction between neighbouring fuel elements, and interactions between bearing pads and pressure tube are not modelled. Also, the calculations do not account for load-shedding along the fuel string and plasticity. For these reasons, this paper reports the maximum stresses developed in the 2 fuel bundles normalized using the highest stress, instead of the absolute stresses.

4. VALIDATION AND VERIFICATION

Mathematical models are often used to study and analyse the performance of CANDU fuel bundles. To have confidence in such simulations, the correctness of the finite-element models used needs to be verified. During the design of HAC, ANSYS finite-element models that simulate the HAC (i.e., 61- element) and the 37-element fuel bundles were developed. These finite-element models were validated by comparing the ANSYS solutions with analytical and test results. The comparisons showed very good agreement. Moreover, these finite-element models have been subjected to additional verifications in this work. Six theoretical solutions of simple rods subjected to different end conditions and to various loads were used to verify these models. Comparisons of ANSYS solutions with these analytical results showed very good agreement again.

5. RESULTS AND DISCUSSION

5.1 Normal Operating Conditions

Figure 5 shows the normalized stresses in the 2 fuel bundles during normal operating and during refuelling conditions.

The results, for normal operating conditions, show that among the end-plate rings the unsupported inner ring is stressed the most. A fuel element on the inner ring has the highest tensile stress among all fuel elements in the fuel bundle. Overall, the highest stress in the fuel bundles is located on the intermediate radial rib, which is located between the supported intermediate ring and the unsupported inner ring.

Comparisons of the calculated stresses in the radial ribs of the end-plate of the 2 fuel bundles show that the stresses in the radial ribs of the CANFLEX fuel bundle are lower than the stresses in the radial ribs of the 37-element fuel bundle. This difference is attributed to the additional radial ribs and to the wider radial ribs in the end-plate design of the CANFLEX fuel bundle, compared with the end-plate design of the 37-element fuel bundle.

Comparisons of the calculated stresses in the rings of the end plates of the 2 fuel bundles show that the stresses in the end-plate rings of the CANFLEX fuel bundle are higher than the stresses in the end-plate rings of the 37-element fuel bundle. This difference in stress is attributed to the support's eccentricity and to the smaller width of the rings of the CANFLEX fuel bundle.

Overall, the 37-element fuel bundle has the highest stress of the 2 fuel bundles for the normal operating conditions.

A number of test cases were run to confirm the trends of these stresses. The conclusion of these analyses is that the additional radial ribs in the end-plate design of the CANFLEX fuel bundle reduce these bending stresses.

5.2 Refuelling Conditions

ANSYS results, for refuelling conditions, show that among the end-plate rings the outer rings of the end plates are stressed the most and that the inner rings are stressed the least in both fuel-bundle designs. Similarly, among end-plate ribs, the highest stress is developed in the outer radial ribs of the end plates, and the lowest stress is developed in the central radial ribs. This analysis also shows that the most stressed fuel element is on the outer ring.

Comparisons of the calculated stresses, in the 2 fuel bundles, show similar trends as in the case of the normal operating conditions. These comparisons are summarized as follows: the stresses in the radial ribs of the end plates of the CANFLEX fuel bundle are lower than the stresses in the radial ribs of the 37-element fuel bundle; the stresses in the end-plate rings of the CANFLEX fuel bundle are higher than the stresses in the end-plate rings of the 37-element fuel bundle; the smaller-diameter fuel elements of the CANFLEX fuel bundle have the highest stress among all fuel elements. As mentioned in the previous section, the differences in the stresses, between the 2 fuel bundles, are caused by differences in the design of the end plates of the 2 fuel bundles and by the differences in the support's eccentricity. Overall, 37-element fuel bundle has the highest stress of the 2 fuel bundles for the refuelling condition.

Comparisons of the stresses of the 2 fuel bundles during refuelling and during normal operating conditions show that the stresses in the fuel sheaths and in the end plates are higher during refuelling conditions. This difference in stress occurs because during refuelling conditions, only 8 fuel elements on the outer ring are supported while the remaining fuel elements are free to move in the axial direction of the fuel bundle. This kind of end condition contributes to additional bending in the end-plate rings.

The maximum stresses in the end-cap-to-fuel element welds are calculated by hand, using the maximum bending moments at the weld locations predicted by ANSYS. The weld diameter is assumed to be equal to end-plate ring or to the inner-rib width. Comparisons of stresses between the 2 fuel bundles show that the highest stress in the welds is developed in the CANFLEX fuel bundle.

5.3 Summary

Version 5.3 of the ANSYS finite-element computer code was used to assess and compare the mechanical strength of the CANFLEX fuel bundle with the mechanical strength of the 37-element fuel bundle during similar conditions: normal operating condition and refuelling condition.

This assessment is summarized as follows (Figure 5):

- Stresses during refuelling conditions are higher than the stresses during normal operating conditions, for both fuel bundles.
- The maximum stresses developed in the 37-element fuel bundle are higher than the stresses generated in the CANFLEX fuel bundle, for both conditions.
- The maximum stress in the end-plate radial ribs of the CANFLEX fuel bundle is about 54% lower than the maximum stress in the end-plate radial ribs of the 37-element fuel bundle during normal operating conditions and about 23% lower during refuelling condition.
- The maximum stress in the end-plate rings of the CANFLEX fuel bundle is about 24% higher than the maximum stress in the end-plate rings of the 37-element fuel bundle during normal operating conditions and about 8% higher during refuelling conditions.
- The maximum stress in the fuel elements of the CANFLEX fuel bundle is about 83% lower than in the fuel elements of the 37-element fuel bundle during normal operating conditions and about 53% higher during refuelling conditions.

5.4 Discussion

The most vulnerable part of a structural or mechanical system is the location where the ratio of the local stress to the local strength is the highest. This ratio is called the stress ratio. The stress ratios for all locations of the 2 fuel bundles have been calculated.

In the 37-element bundle, the highest value of stress ratio occurs in the end-plate ribs; hence that is the most vulnerable location in a 37-element bundle. Note that this is also the location where the 37-element bundle failed in the Darlington reactor because of axial vibrations driven by pressure pulses in the coolant [5]. This situation has been eliminated in the Darlington reactor by reducing or eliminating the resonance of fuel strings. Note that there has never been any indication that a similar problem might exist in the CANDU 6 reactor.

The adequacy of the strength of the 37-element fuel bundle has been demonstrated by many hundreds of thousands of bundles that have been successfully irradiated, to date, in the commercial CANDU reactors. Therefore, the 37-element fuel bundle has acceptable values of stress ratios at all locations.

To obtain a comparative indication of the relative strengths of the CANFLEX bundle compared with that of the 37-element bundle, we have normalized all stress ratios to the highest value calculated for the 37-element bundle. The resulting number is called the normalized stress ratio, and it is shown in Figure 6 for all locations of the 2 fuel bundles.

Based on the location of the highest stress ratio, the most vulnerable location in the CANFLEX bundle is the outer-end-plate ring. The highest stress ratio in the CANFLEX bundle is about 93% of that in the 37-element bundle. Therefore, the relative strength of the CANFLEX bundle is about 7% higher than that of the 37-element bundle.

6. CONCLUSIONS

It has been demonstrated in a number of irradiations that the 37-element fuel bundle has adequate mechanical strength to withstand the loads that are expected during normal and refuelling operations. Overall, for the analysed conditions, the 37-element fuel bundle has the highest stress of the 2 fuel bundles, and the relative strength of the CANFLEX bundle is about 7% higher than that of the 37-element bundle.

7. ACKNOWLEDGEMENTS

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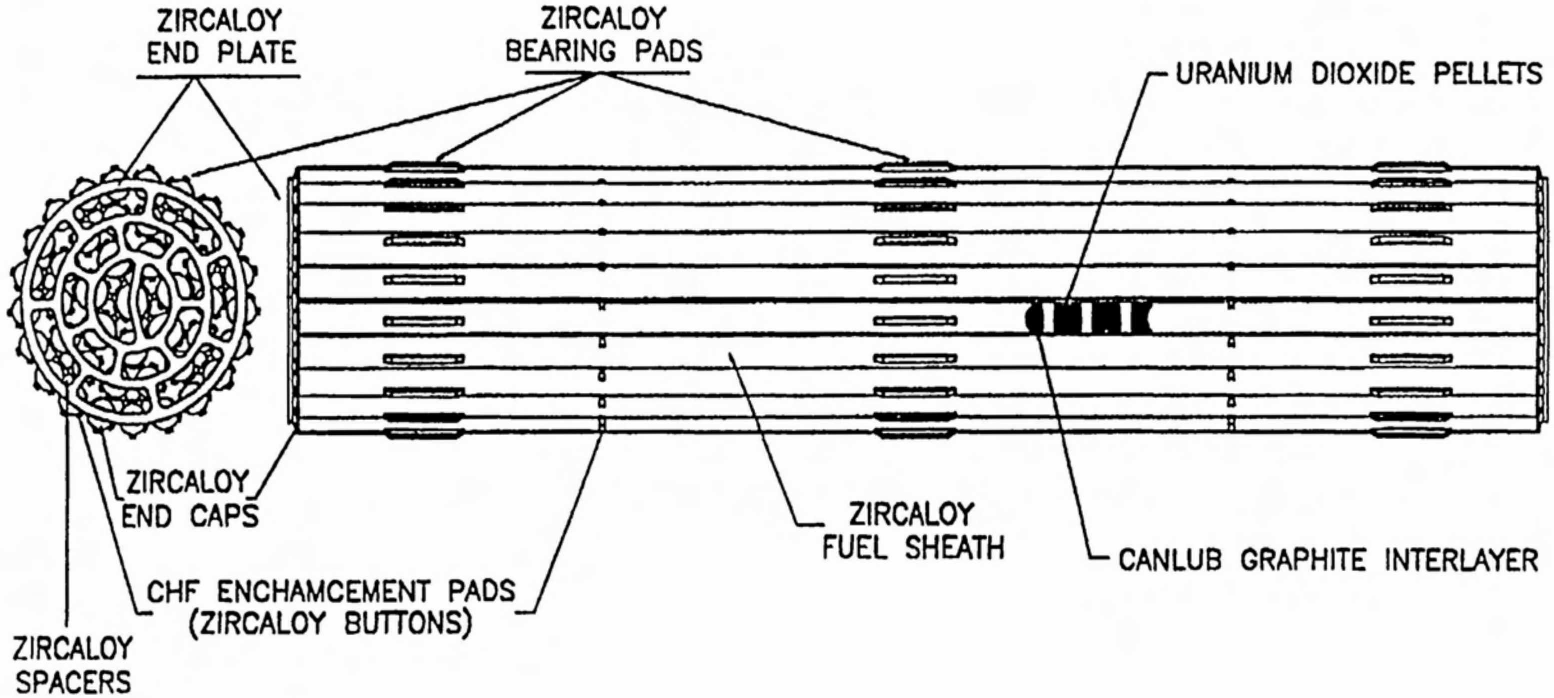


FIGURE 1: CANFLEX 43-ELEMENT FUEL BUNDLE

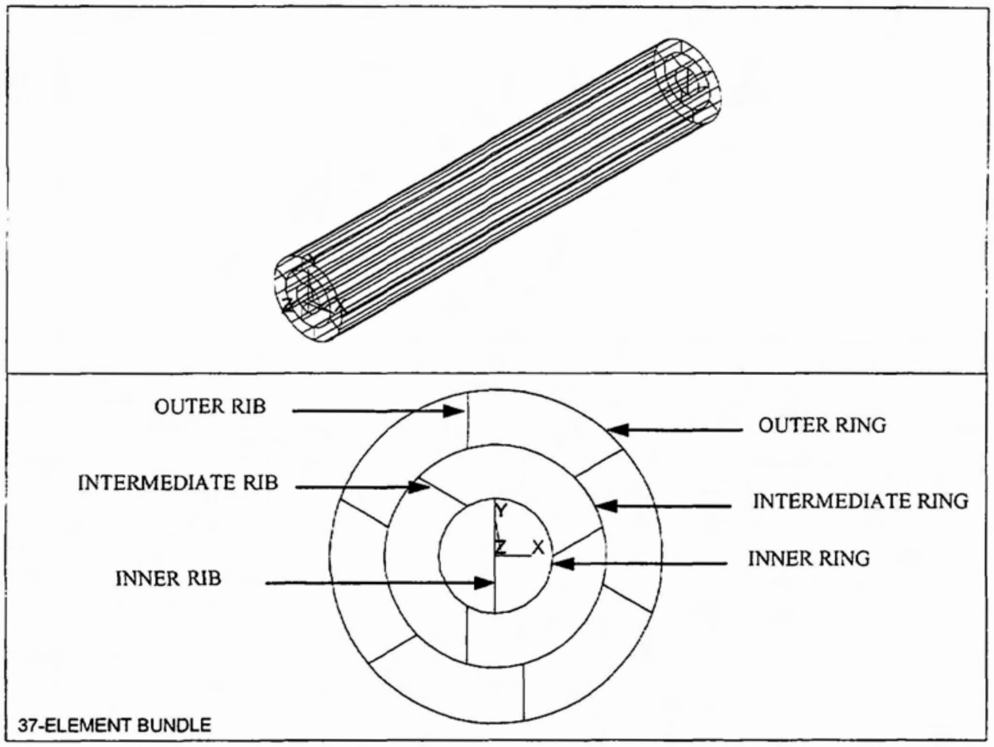


FIGURE 2: 37-ELEMENT FUEL-BUNDLE MODEL

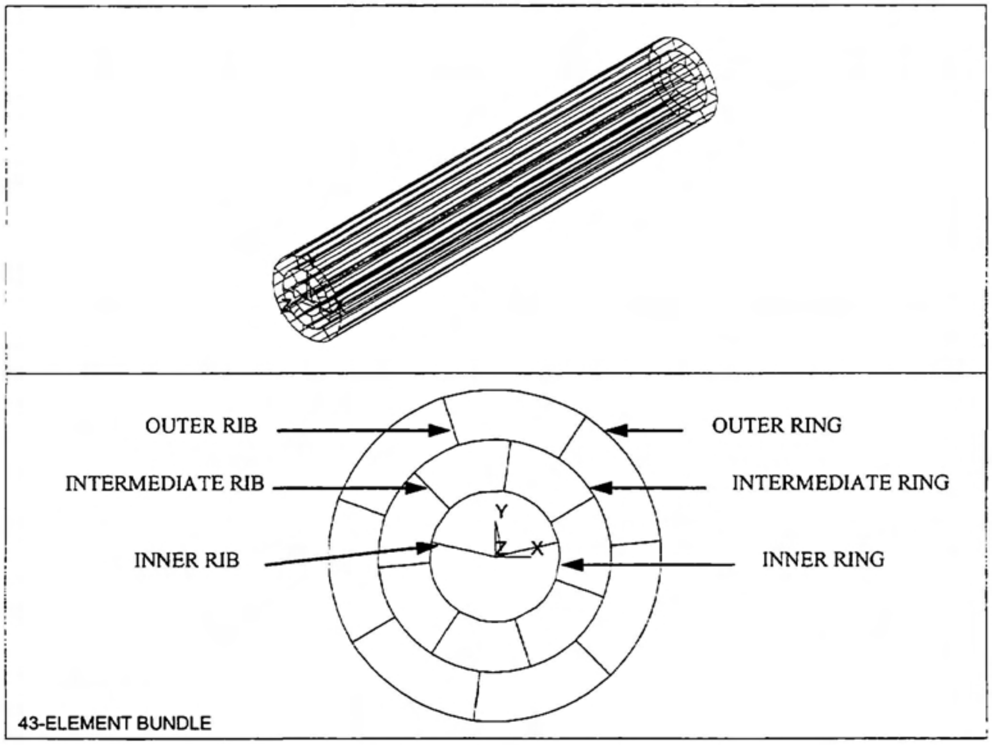
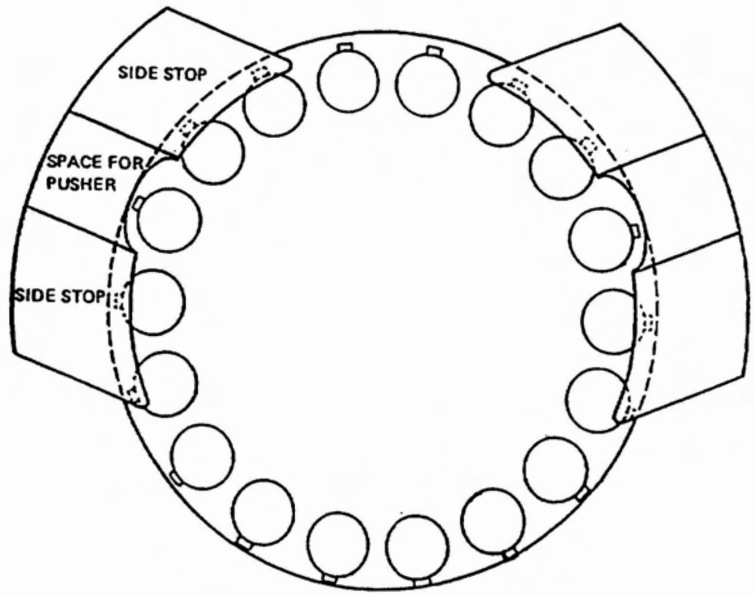


FIGURE 3: CANFLEX FUEL-BUNDLE MODEL



SHIELD-PLUG

END-PLATE

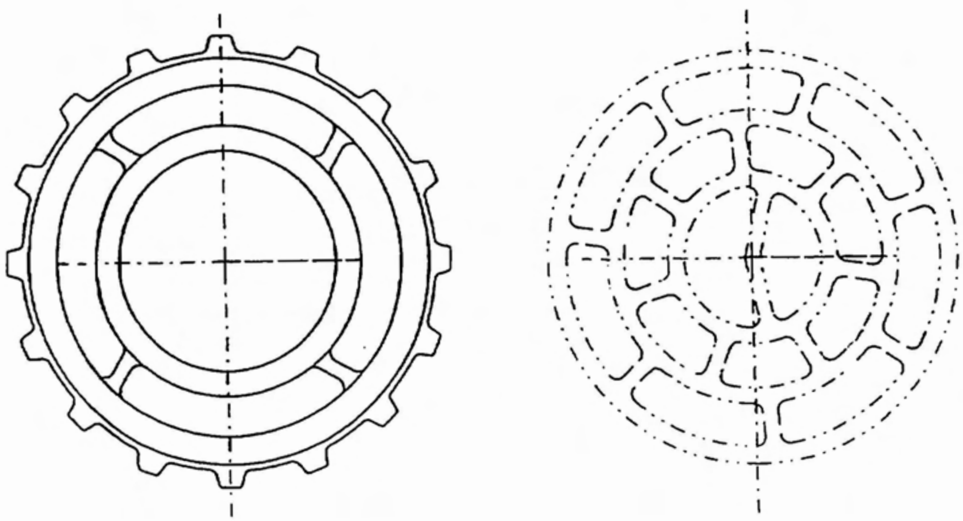


FIGURE 4: SIDE STOPS AND SHIELD-PLUG SUPPORTS

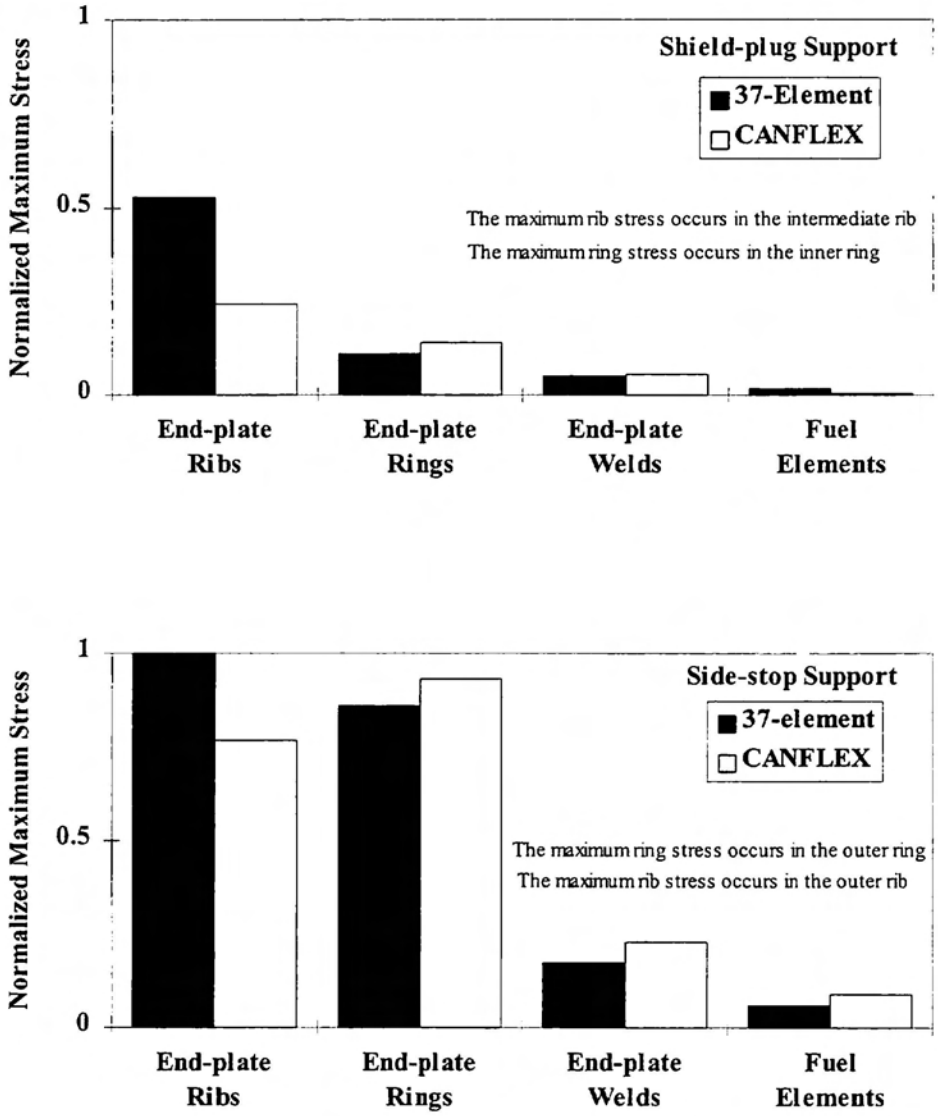


FIGURE 5: NORMALIZED STRESSES IN THE FUEL BUNDLES

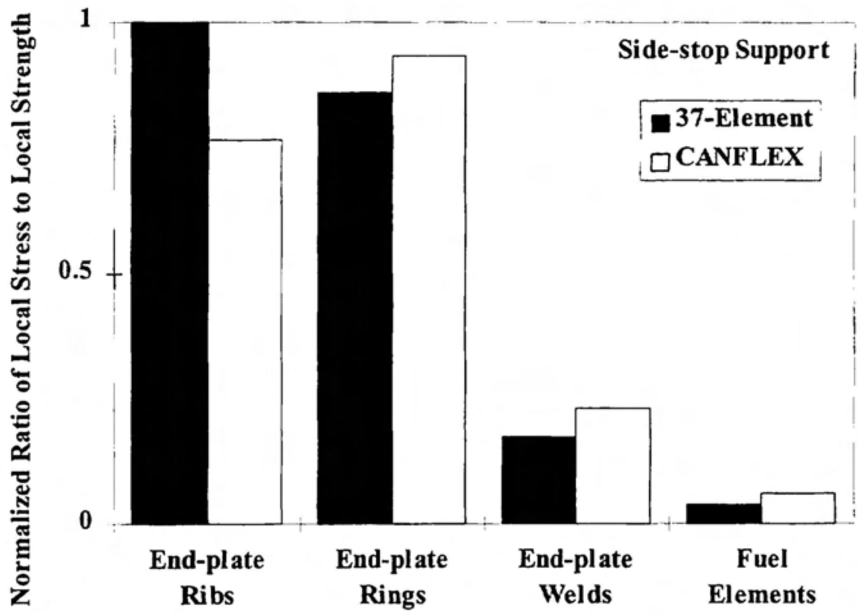


FIGURE 6: STRESS RATIOS IN 37-ELEMENT AND CANFLEX FUEL BUNDLES