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# Structural analysis of plate-type fuel assemblies and development of a non-destructive method to assess their integrity

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## HIGHLIGHTS

- A plate-type fuel assembly is made of thin plates mounted in a box-like structure.
- Drag force from the coolant can shift the plates.
- A non invasive method is proposed to test the strength of the plate connections.
- The natural frequencies' shift is used to assess the fuel integrity.

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## ABSTRACT

This work is concerned with the structural behaviour and the integrity of parallel plate-type nuclear fuel assemblies. A plate-type assembly consists of several thin plates mounted in a box-like structure and is subjected to a coolant flow that can result in a considerable drag force. A finite element model of an assembly is presented to study the sensitivity of the natural frequencies to the stiffness of the plates' junctions. It is shown that the shift in the natural frequencies of the torsional modes can be used to check the global integrity of the fuel assembly while the local natural frequencies of the inner plates can be used to estimate the maximum drag force they can resist. Finally a non-destructive method is developed to assess the resistance of the inner plates to bear an applied load. Extensive computational and experimental results are presented to prove the applicability of the method presented.


## 1. Introduction

Parallel plate-type fuel assemblies (PTFA) are commonly used in reactors where a high neutron flux is desired. This is the type of fuel assembly used in the OPAL pool-type nuclear research reactor at the Australian Nuclear Science and Technology Organisation (ANSTO). A typical PTFA is fabricated as a box-type structure containing around twenty thin plates with a nuclear core material. Two side plates perpendicular to the thinner fuel plates, have a series of slots into which the fuel plates are inserted and fixed by a technique known as "roll swaging", where a sharp edged swaging wheel is pressed into the ridge between grooves, plastically deforming the ridge on to the fuel plate and fastening it in place. The swage joints prevent both the PTFA from coming apart laterally and the plates from sliding out due to the drag force induced by the flow.

During a routine shut down in July 2007 after 5 operating cycles in the OPAL reactor it was noticed that some of the fuel plates within the OPAL Fuel Assembly (FA) had displaced in the direction of the flow (ANSTO, 2007a,b). Extensive investigations showed that operating conditions were not linked to the event and that reactor component vibration levels were as previously measured during commissioning. It was then suggested that the sole reason for the translation of the fuel plates was due to low strength swaging that allowed the plates to slide along the slots. Those concerns motivated the aim of this work, that is, to develop a method to assess the strength of the swages in PTFAs.

In the past much research interest has been devoted to understand the vibrations of nuclear fuel assemblies but the work published are mainly concerned with the global behaviour of the core (Planchard, 1985) or about the flow induced vibrations and related instabilities (Blevins, 1979; Guo and Paidoussis, 2000; Kim and Davis, 1995; Païdoussis, 1983). Rod fuel assemblies have also been investigated (Choi et al., 2004; Premount, 1982; Zeman and Hlaváč, 2011). The number of published work related to PTFA is very scarce and is focused on fluid dynamics aspects (Cui et al., 2008; Gwaltney and Luttrell, 1988; Kim and Davis, 1995; Païdoussis, 2004; Pavone and Scarton, 1982; Wang et al., 2004). To the author's

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knowledge there are no methods readily available to perform a quality check of a PTFA. Considering the number of safety issues and very high costs involved in a failure of a PTFA during operation, this is a matter well worth investigation.

The development of a non-destructive method to assess the quality of the swages and the structural integrity of PTFAs is strictly related to the findings of the authors published in recent works (Caresta and Wassink, 2012a,b). In particular Caresta and Wassink (2012a) showed that the swage joint stiffness can be related to both the natural frequencies of a plate and to the force needed to pull it out from its fabricated position The relationships were found by using an experimental rig that reproduced a variable form of the joint conditions in the assembly. In summary it was concluded that a stiffer joint results in higher natural frequency and a higher force to slide a plate out from its location. The idea was then to transfer these findings to a real FA. It was clear that the chance of applying the results of Caresta and Wassink (2012a) was highly related to the possibility of measuring the natural frequencies of the inner plates of a FA. This problem was solved by developing a method to estimate the natural frequencies of a plate by using a single point measurement as detailed by Caresta and Wassink (2012b). Considering the importance of safety in nuclear plants, the difficulties from a modelling point of view and more importantly, to the issues on testing nuclear fuel structures with a very small freedom and many constraints, this work gives an important contribution to the understanding of the structural behaviour of PTFAs. The method presented to assess the quality of a PTFA can be used both by manufacturers and nuclear plant operators. Furthermore, many interesting structural phenomena were found during testing such as mode localisation, periodic structure and non-linear behaviours, all aspects that deserve further investigation. Section 2 presents an analysis of a FA seen as a whole structure. The finite element method was used to predict the vibrational characteristics which were compared with results from experimental tests. It is shown that the variation of the natural frequencies of the torsional modes gives a first indication of an average quality of the swages. Section 3 is focused on the behaviour of the inner plates and their decoupling from the rest of the assembly. The paper is concluded by Section 4 where the method to assess the quality of the FA is detailed.

## 2. Model of a FA

Fig. 1 shows a picture of a typical FA with a close up of the swage joints. The grooved side plates and external fuel plates are fixed to the end box seen at the bottom of the FA in Fig. 1 (left). The end box and therefore the FA are fixed securely to the reactor core grid.

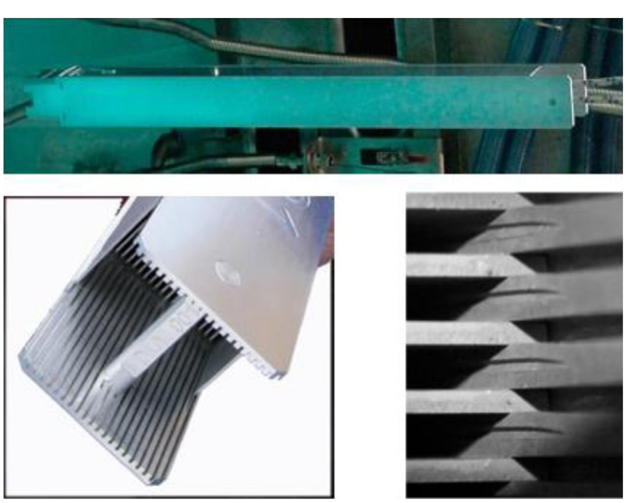

**Fig. 1.** The OPAL PTFA: lateral view (top), swage joint detail (lower right), top view (lower left).

The key aspect on modelling the FA is the connection of the inner plates to the side plates. It was recently shown by the authors that the connection of the fuel plates can be modelled as a rigid clamp except for the rotational degree of freedom around the axis of the swage, constrained by a torsional spring with a stiffness dependent on the quality of the swage itself (Caresta and Wassink, 2012a). A finite element model was built with the FE MD-Patran/Nastran software package to predict the dynamic behaviour of the assembly. The base was meshed using Tet-4 solid elements and the inner plates were meshed using 4-node elements. The central part of the fuel plates was modelled using composite material made of three layers, uranium silicide ($U_3Si_2$) in the middle covered by two layers of aluminium. The swage joints were modelled using bush elements with six degrees of freedom, assigning a very high value of stiffness in all directions except for rotation around the side edges.

### 2.1. Sensitivity analysis of the natural frequencies to variation in swage quality

The quality of the swage is simulated assuming variable torsional spring stiffness for the joints. The assembly was fixed at the shoulder of the end box. The first natural modes are shown in Fig. 2 and can be classified as bending in the $x$ and $y$ direction and torsional along the longitudinal $z$ direction. Fig. 3 shows the variation of the natural frequencies with respect to the torsional spring value that was used to simulate the swaging quality. The values of the natural frequencies were normalised with respect to those of a perfect clamp. It can be seen that the bending modes in the $x$-direction are not affected by the swaging quality. The sensitivity of the modes in the $y$-direction increases with the mode order but the highest sensitivity is shown by the torsional modes. This result is not surprising if we consider that during a torsional motion, the stress is concentrated at the side connection of the plates (Fig. 4). The FA is basically kept torsionally stiff by the plate's connections, therefore looseness results in a loss of strength, affecting the torsional behaviour.

These results are useful to estimate the global quality of a FA and to compare it to a theoretical model or more precisely, to a reference FA considered or proven to be of excellent quality. This aspect is considered in the next section.

### 2.2. Modal analysis of a FA

As shown before, the quality of the swaging affects the structural response of the whole FA. A modal analysis was performed on a set of five uranium loaded FAs in order to detect any variation in natural frequencies that could indicate poor swage quality. A FA was clamped to a specially designed heavy base as shown schematically in Fig. 5. Excitation was provided with an impact hammer in the $y$-direction and the frequency response function (FRF) of the velocity was measured for several points along the length of the assembly. Measurements of the velocity response were made using a laser vibrometer focused on the edge of the side plates.

The mode shapes were identified by standard quadrature peaking (Ewins, 2000). The 3rd torsional mode is of primary interest and the shape is reported in Fig. 6 showing good agreement with the FEM mode shape, but showing a considerable drop of the natural frequency due to the difference between the inner plate joint stiffness compared to ideal stiffness. The lines in Fig. 6 represent two of the edges of the assembly.

The FRFs for the five FAs tested are shown in Fig. 7. As observed in the previous section, it can be seen that basically no variation is evident for the 1st and 2nd bending modes. However, a variation between 14% and 23% can be observed for the torsional modes. A