Development and IAEA IWGFR Benchmarking of an Abaqus-Based Core Bowing Analysis System for SFR Fuel Assemblies

Heung Soo Lee*, June-Hyung Kim, Cheol Min Lee, Juseong Kim, Jin-Sik Cheon, Byoung Oon Lee, Chan Bock Lee
Advanced Fuel Technology Development Division, Korea Atomic Energy Research Institute, Daejeon, 34057, Korea

*Corresponding author: hslee88@kaeri.re.kr

**Keywords : sodium-cooled fast reactor, fuel assembly bowing, core restraint, IWGFR benchmark*

1. Introduction

In a sodium-cooled fast reactor (SFR) core, the hexagonal ducts of the fuel assemblies bow under cross-duct temperature gradients and, as burnup accumulates, under irradiation swelling and creep. Assembly bowing governs the geometric component of the power–reactivity feedback, the withdrawal loads at refueling, and ultimately the design of the core restraint system, so a validated bowing analysis capability is a prerequisite for SFR core design.

As part of an effort to establish such a capability, we are developing an Abaqus-based assembly-bowing analysis system. For validation we adopt the IAEA IWGFR benchmark set, produced by a Coordinated Research Programme (1986–1989) in which about ten national codes solved a common series of core mechanics problems [1,2]. The benchmark ladder proceeds from single-assembly thermal bowing to a full-core problem combining swelling, irradiation creep, and inter-assembly contact. This paper briefly describes the modeling approach and the current validation status.

2. Analysis System and Modeling

The system consists of a parametric core builder, automated model generation, and automated verdicts. A hexagonal-lattice generator produces a core with an arbitrary number of hexagonal rings N around the central assembly (1+3N(N+1) assemblies in total), together with exact mirror/rotation mappings, so that the same machinery scales from a single assembly to the full 127-assembly (N = 6) core of Fig. 1. Post-processing compares the results against acceptance values registered before each run, and the pure-calculation layer is locked by an automated regression suite.

Each duct is modeled as a column of 3-D beam elements (B33) with a thin-walled hexagonal section, supported at the lower nozzle by displacement supports and a rotational spring. Thermal bowing is driven by nodal temperatures with prescribed cross-section gradients. Irradiation swelling enters as a dose-proportional eigenstrain through a nodal field carrying the local dose D(r, z), and irradiation creep through a dose-based creep law integrated quasi-statically over the dose history. Contact at the load-pad planes and at the restraint rings is represented by gap–spring elements, and the contact loads are recovered from the converged displacements.

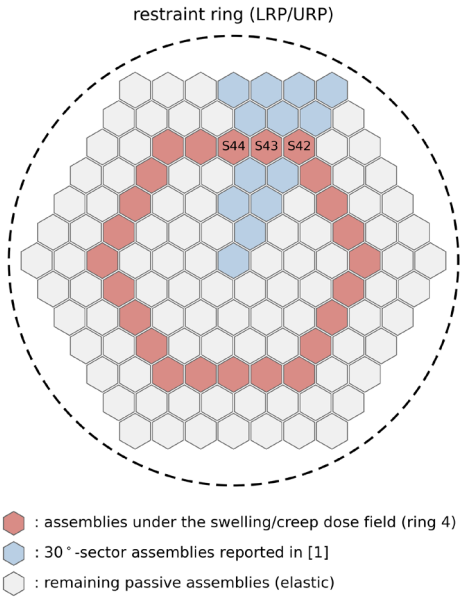


Fig. 1. 127-assembly core model produced by the parametric lattice builder (IWGFR/75 Example 5). Red marks the assemblies subjected to the swelling/creep dose field, blue the 30-degree sector assemblies reported in the benchmark, and grey the remaining passive assemblies. The dashed circle is the restraint ring acting at the lower and upper restraint planes (LRP/URP).

3. IWGFR Benchmark Validation

Table 1 summarizes the validation ladder. The single-assembly thermal bowing problems (Ex. 1/2) reproduce the closed-form tip deflections to within 10^{-4} %. The 16-assembly thermal contact problem (Ex. 3A) agrees with the participant mean displacement to 0.005 mm once the gap-at-temperature convention of the participating codes is applied. The swelling free-bow (Ex. 7A) and creep (Ex. 8A) problems reproduce their analytic solutions essentially exactly.

Table 1. IWGFR benchmark validation status (deviations from the reference solutions)

Problem	Physics	Reference	Result
Ex. 1/2	thermal bowing, single S/A	closed form 12.250/16.333 mm	$\leq 10^{-4}$ %
Ex. 3A	thermal bowing + pad contact, 16 S/A	9-code mean 8.54 mm	8.536 mm (in band)
Ex. 7A	swelling free bow	closed form	$\leq 10^{-3}$ %
Ex. 8A	irradiation creep (plate strip)	closed form 8.401/8.459 mm	$\pm 10^{-4}$ %
Ex. 5	swelling + creep + contact, 127 S/A	7-code averages/band	loads +0.5/+1.7 %, displ. at lower edge of band

The highlight is Ex. 5, in which the ring-4 assemblies of a 127-assembly core (Fig. 1) swell and creep under a prescribed dose field against a passive restraint system. Fig. 2 shows the computed dose history. The restrained bowing displacement saturates once the pad gaps close, after which the contact loads continue to grow — i.e., the late-dose response is geometry-locked. At 100 dpa the computed S/A42 upper-restraint displacement, 1.326 mm, lies at the lower edge of the band reported by the participating codes (1.33–1.34 mm at the 0.01 mm resolution of the benchmark tables), and the computed pad loads, 994.6/1171.3 N, agree with the participant averages (990/1152 N) to +0.5 %/+1.7 % against a participant spread of 11 %. Although all 127 assemblies are solved independently with no symmetry condition imposed, the computed solution reproduces the 30-degree symmetry of the problem — the displacements of symmetry-equivalent assemblies agree to within 0.001 %.

4. Summary

An ABAQUS-based assembly-bowing analysis system has reproduced the IAEA IWGFR benchmark ladder — thermal bowing, pad contact, swelling, irradiation creep, and their full-core combination — within the scatter of the original international participants. Work in progress includes the transient checkpoint comparison of the full-core problem and the documentation of the verified example set. The system will next be applied to prototype core restraint studies, replacing the benchmark material laws with design correlations through the same field/creep interfaces.

ACKNOWLEDGEMENT

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (Ministry of Science and ICT, No. RS-2025-25455699)

REFERENCES

[1] International Atomic Energy Agency, Verification and Validation of LMFBR Static Core Mechanics Codes, Part I, IWGFR/75, IAEA, Vienna, 1990.
[2] International Atomic Energy Agency, Verification and Validation of LMFBR Static Core Mechanics Codes, Part II, IWGFR/76, IAEA, Vienna, 1990.
[3] Dassault Systèmes, SIMULIA User Assistance — Abaqus, 2025.

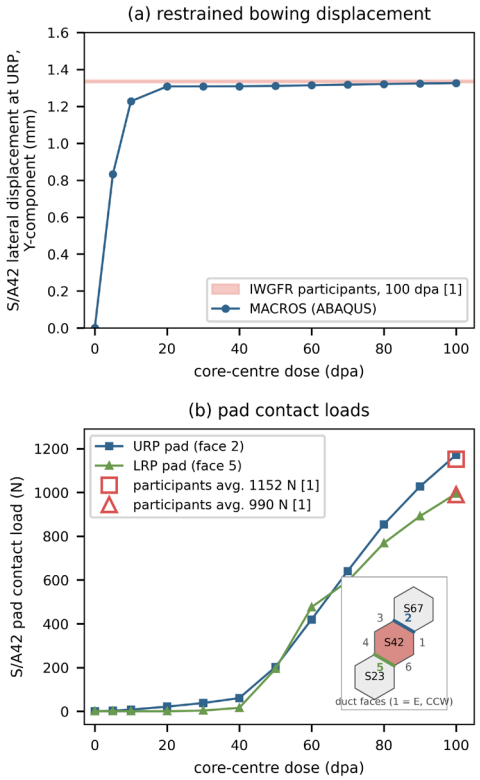


Fig. 2. Computed dose history of S/A42 in Example 5. (a) Restrained bowing displacement at the upper restraint plane (Y-component, the quantity tabulated in the benchmark) with the band reported by the participants at 100 dpa. (b) Pad contact loads on duct faces 2 (URP) and 5 (LRP) with the participant averages. The inset shows the duct face numbering of the benchmark (face 1 = east, counterclockwise) and the neighboring assemblies across the two loaded faces.