Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 6023

Bending test device for mechanical integrity studies of spent nuclear fuel rods

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Abstract

This paper presents data obtained from experiments performed using a bending test set-up developed at the Joint Research Centre (JRC) – Karlsruhe, for spent fuel segment testing. Adjustable sample holders, loading modes and other experimental conditions can be implemented in the experiments to study the effects of different deformation ranges up to cladding failure. The experimental set-up has been adapted to hot cell remote controlling and has a modular configuration, which allows manual and motor-driven loading option. The device has been calibrated on hydrogenated, unirradiated cladding tube segments filled with alumina pellets. The final application of present set-up is to test non-defueled spent fuel rod segments, pressurized to the original spent fuel rod pressure level. The range of applicability of this device, the scope of the experimental program and the first results from actual bending tests will be discussed.

Introduction

The properties of nuclear fuel rods change significantly during their operational life in a nuclear reactor under the effect of irradiation and of the thermo-mechanical conditions in the reactor core. Further changes may occur after discharge from the reactor due to heating-cooling processes and to the cumulative effects of radioactive decay damage in the material. These modifications may affect the response of spent fuel rods to mechanical solicitations corresponding to normal conditions and accident scenarios.

An essential requirement for the safety of spent nuclear fuel (SNF) is that the mechanical integrity of the fuel rod is maintained during the handling, storage and transportation steps associated with spent fuel management. The assessment of specific aspects and processes expected to affect properties and behaviour of spent fuel during transportation and storage includes direct measurements on spent fuel rods and segments.

For this purpose, an experimental device for 3-point bending tests has been developed in JRC-Karlsruhe. The main objective is to examine the effects of external loads on the behaviour of a non-defueled spent fuel rod segment by determining various mechanical properties.

The experimental campaign has been divided mainly in two parts. The first part consists of "cold" analogue tests performed using hydrogenated Zircaloy-4 (Zr4) cladding tubes. The cladding tubes are pressurized and filled with high purity Al_2O_3 pellets. The "cold" experimental campaign will be used for simulation validation purposes and for the device optimization process. The second part of the campaign includes experiments in hot-cell on SNF rods that have been irradiated in a Swiss pressurized water reactor (PWR). The fuel rod segments under investigation will cover a wide range of burnup.

Similar projects have been performed by conducting mechanical tests to characterize properties of the compound system of fuel and cladding material [1-3], some of them accompanied by finite element analysis (FEA) calculations [4, 5]. The specific feature of this campaign is the fuel selection which includes a wide range of burnup, UO_2 and also MOX and the accompanied pre and post-test examinations on the SNF in order to fully characterize its behaviour.

This paper describes the configuration of the bending setup along with its acquisition capabilities, and the outcome of the preliminary tests performed to demonstrate and optimize the performance of the device in view of its installation in hot cell and use on spent fuel rod segments. Some trends observed during this first series of the cold experiments will be schematically discussed. Finally, the upcoming experimental campaign on spent fuel segments will be introduced.

Experimental Apparatus

The experimental device is shown in Fig.1. The device consists of a step-motor which drives a loading column along a vertical axis, perpendicular to the sample orientation. The loading column has a concave contact surface which is adjusted to the cladding surface of the fuel rod sample. The modular design of the device allows the use of different loading contact components. A load sensor measures the load applied to the cladding surface. The sample supporting points could be placed at different distances. This provides a great flexibility for measuring samples of different lengths.

Data acquisition is performed by using three different sensors to measure the applied load, the deflection and the internal pressure of the segment. The sample, either the hydrogenated unirradiated zircaloy cladding or a segment from a spent fuel rod, is pressurized to reproduce the conditions that a spent fuel rod experiences.

The geometrical configuration of the device follows the prerequisites of a standard bending test as specified in the ISO 7438 standard. The distance between the centres of the supports is 140 mm and the maximum deflection that can be achieved is 75 mm. This corresponds to a bending angle of approximately 115^{o}.

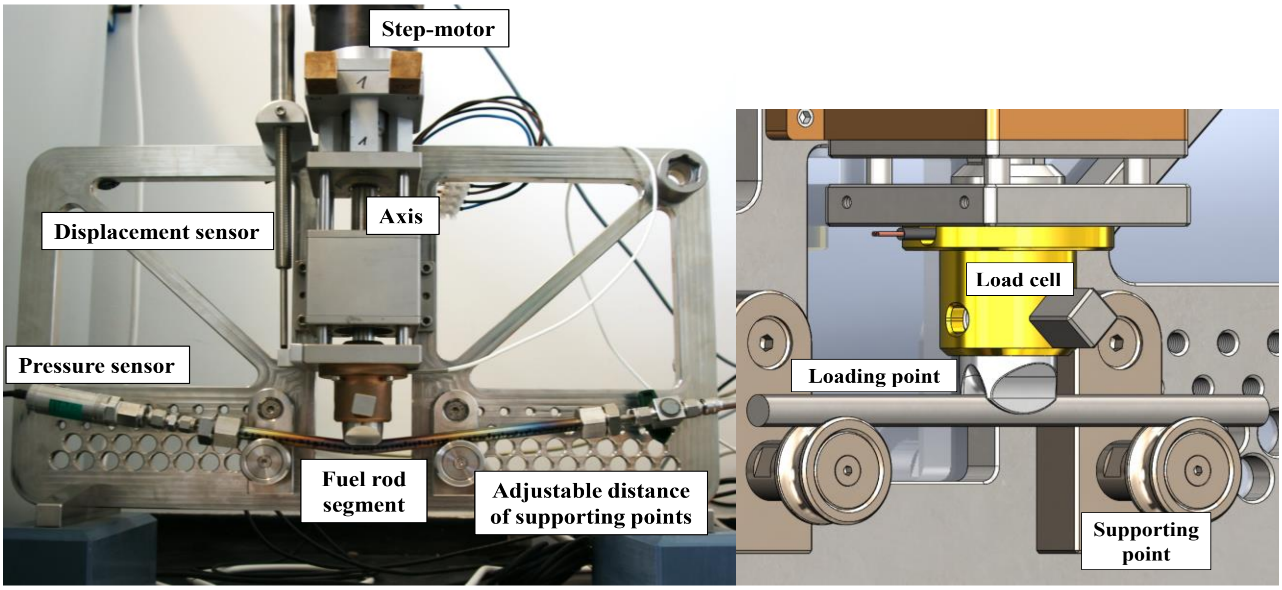


Figure 1 Experimental device for quasi-static 3-point bending test.

The sensors are connected to a real time hardware platform which features a range of embedded controllers with two processing targets: a real-time processor for communication and signal processing and a user-programmable field program gate array (FPGA) to implement high-speed control and custom timing and triggering directly in hardware. A graphical user interphase has been developed for controlling the step-motor and acquiring the signals from the sensors. This program is able to activate the step-motor and control the displacement velocity of the loading point. In addition, a graphical environment has been developed in order to provide real-time observation of the measured values.

Cold Test Campaign

Analogue studies have been performed before the employment of the spent fuel rods. This cold test campaign is also supported by collaboration with the German Federal Institute for Materials Research and Testing (BAM). BAM's extensive expertise in mechanical modelling with the use of finite element analysis [7] provides essential contribution for model validation purposes [8].

Sample characteristics and preparation

A typical hydrogenated pressurized Zr4 cladding sample is shown in Fig.2. The cladding material is a conventional Zircaloy-4 (Zr4) tube with known impurity concentrations. The Zr4 cladding tubes used in the present work had an outer diameter of 10.75 mm, wall thickness of 0.725 mm and a total length of 298 mm. The cladding tubes were filled with high purity aluminium oxide pellets of known mechanical properties, having a diameter of 9.27 mm and length of 10 mm. This gives a radial gap between the cladding and the pellets of 0.015 mm. The samples were pressurized up to 40 bar with He gas.

Figure 2 Pressurised hydrogenated Zr4 cladding tube used for the 3-point bending experiments.

The selection of this internal pressure of the sample is based on experience accumulated at the JRC-Karlsruhe through numerous puncture test measurements on irradiated commercial fuel rods and is corroborated by a semi-empirical formula provided in [6]. This EPRI report describes the end-of-life rod internal pressure (RIP) for different PWR fuel types. The selection of 40 bar is representative of a burnup value around 50 GWd/MTU, which, in turn, can well represent the average burnup of a Swiss PWR fuel assembly.

The hydrogenated cladding samples were provided by the Institute of Applied Materials (IAM) of the Karlsruhe Institute of Technology (KIT). The hydrogenation method applied to the samples is described in [9, 10]; the samples were hydrogenated at temperatures of 550, 650 and 750^{o}C, respectively. The treatment resulted in a hydrogen concentration distribution along the axis that was determined by measuring diameter variations. A typical graph of the hydrogen axial concentration profile of a sample is given in Fig.3. The loading point on the sample was chosen in region of pre-selected hydrogen concentration. As much as possible, multiple tests were performed at similar hydrogen concentration levels in order to improve the statistics of the results.

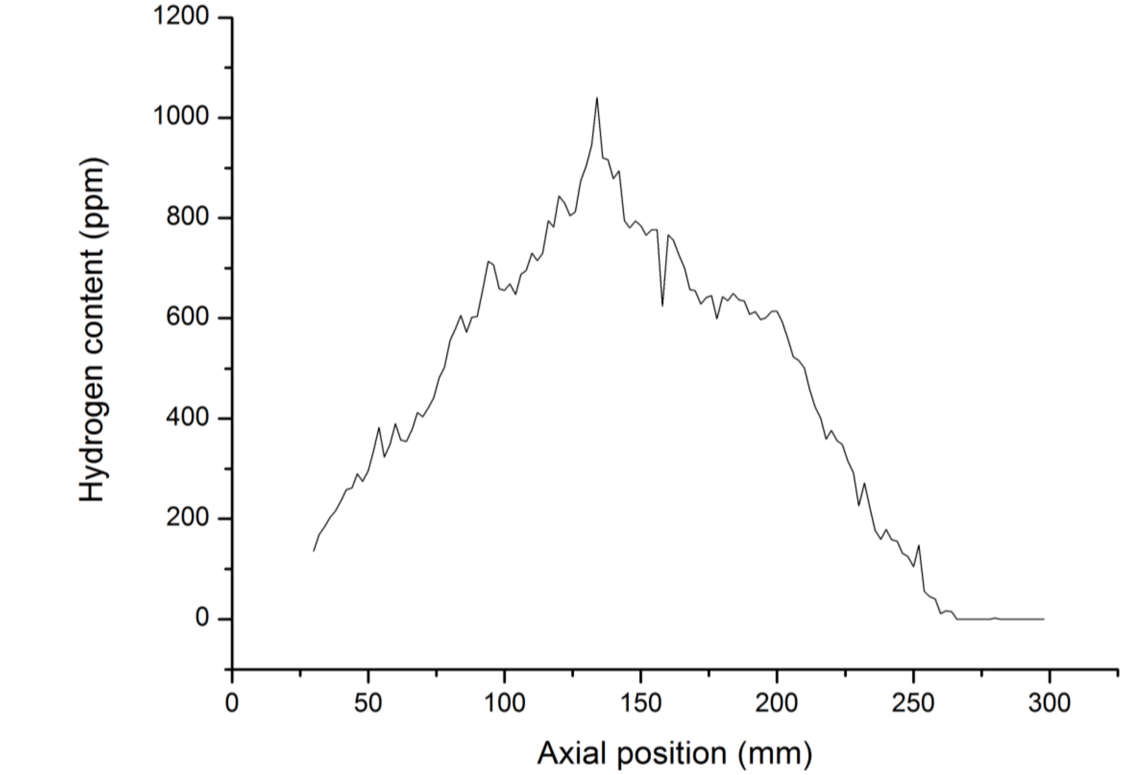


Figure 3 Hydrogen concentration axial profile of a sample used for the bending test.

Results and Discussion

The present experiments were aimed mainly at demonstrating and optimising the capabilities of the testing setup in view of its application to characterise deformation and failure behaviour of spent fuel rods. It is well known that the hydrogen content in spent fuel cladding is a key factor affecting the response of the fuel rod to mechanical solicitations and loading that may occur during the various stages of spent fuel management. To verify the effectiveness of the bending setup in characterising such effects, the cold test campaign covered a wide range of local hydrogen concentration levels, from very low (including untreated cladding) to extremely high content (>2000 ppm). In total, twenty experiments have been conducted on pre-hydrogenated samples for the present cold test campaign. The pressure, the applied load and the deflection of the sample at the loading point were acquired for each experiment. Typically, a constant displacement rate of 125 µm/s was used. The evolution of the data values acquired during the test provides information from the first contact to the point when the cladding tube cracks and the pressure and applied load drop. Fig.4 illustrates the typical results of one of those experiments, performed on a sample with local hydrogen content of 236 ppm; in the graph, load and internal pressure are plotted as a function of deflection. The slow pressure decrease during the experiment, and before the cladding tube cracks, is a consequence of the slow increase of the sample’s volume during its deformation. One can distinguish also the elastic and plastic deformation regions. Moreover, the strain energy submitted to the sample by the loading device can be calculated from the area under the curve and the critical energy until fracture can be estimated. Also, the ultimate and fracture strength can be calculated. Details of small discontinuities observed in the plastic deformation region of the load vs. deflection curve are highlighted in the inset shown within Fig.4. The relatively small drops of the load can be attributed to cracking occurring in the alumina pellets under the load applied during the experiment. Such cracking could be heard during the tests.

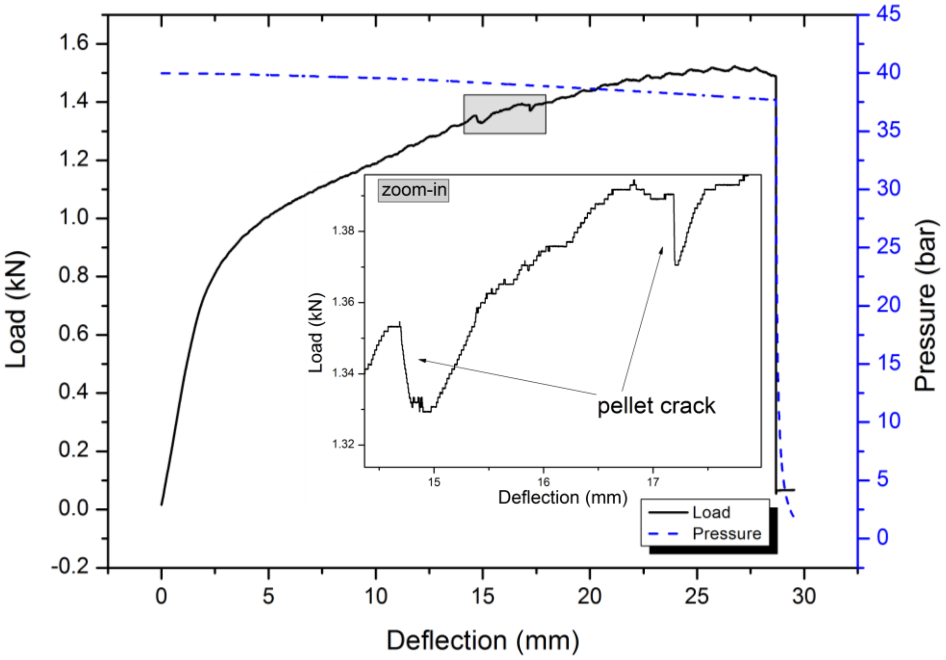


Figure 4 Load/Pressure vs. Displacement during a 3-point bending test.

In Fig.5 the deflection at which the sample fractures is plotted as a function of the local hydrogen content for all the experiments performed on hydrogenated samples. The effect of varying hydrogen concentration is clearly visible on the diagram.

At very low hydrogen content (≤ 100 ppm) the cladding has preserved its ductility and requires a large deflection in order to be fractured. In this case, the presence of the dummy alumina pellets inside the samples seems to contribute to the fracture. In the same deformation range that causes fracture of samples loaded with dummy pellets, Zr4 cladding tubes with the same hydrogen content but without pellets inside did not fracture**.** For hydrogen content up to around 700 ppm (which includes the hydrogen content range to be expected in commercial spent fuel cladding) a linear correlation between the local hydrogen content and the deflection range could be observed. This region is detailed in the inset within Fig.5. At higher hydrogen content the samples break at the same deflection level independently of the local hydrogen content. The cladding material in this range can be described as brittle and the fracture of the sample occurs more abruptly.

Post-test examination was performed on the samples. Examination of the fracture indicated, as expected, that the samples cracked preferentially at the pellet-pellet interface nearest to the loading point and not exactly at the point of the theoretical maximum applied load, i.e. at the axial position under the loading contact point. This confirms the high significance of the fuel pellets presence, which affects the response to the mechanical load of the fuel-cladding system.

Hydrogen measurements with the method of hot gas extraction will be carried out on selected samples at the point of fracture to determine the local hydrogen concentration to confirm the nominal content and support the conclusions from the observed trends. These additional analyses will be performed also on the very few outliers from these tests.

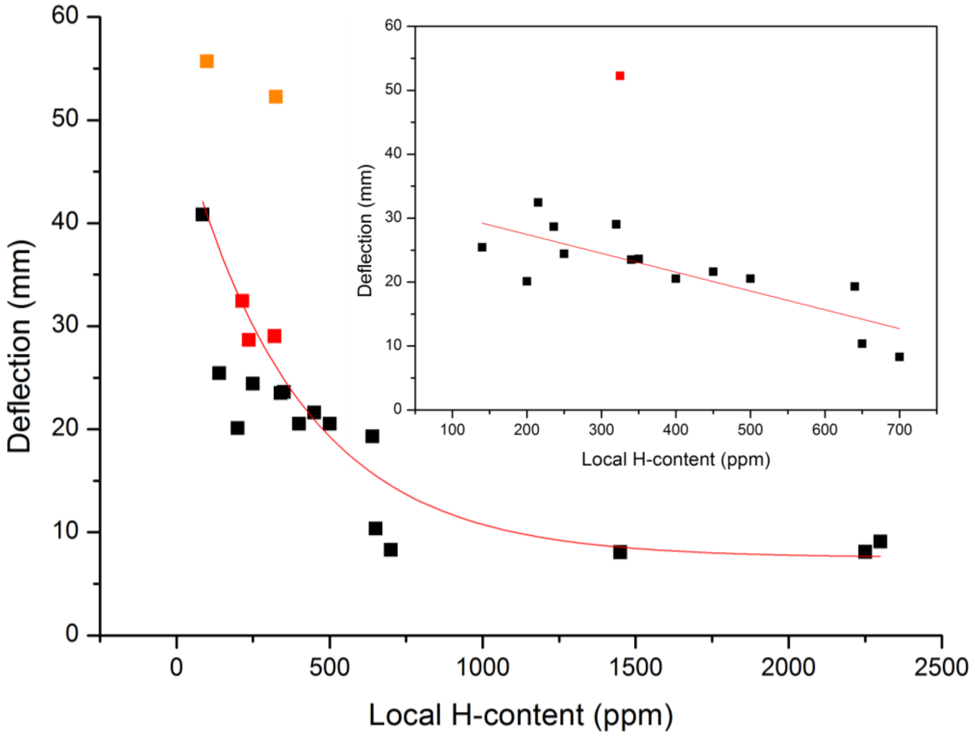
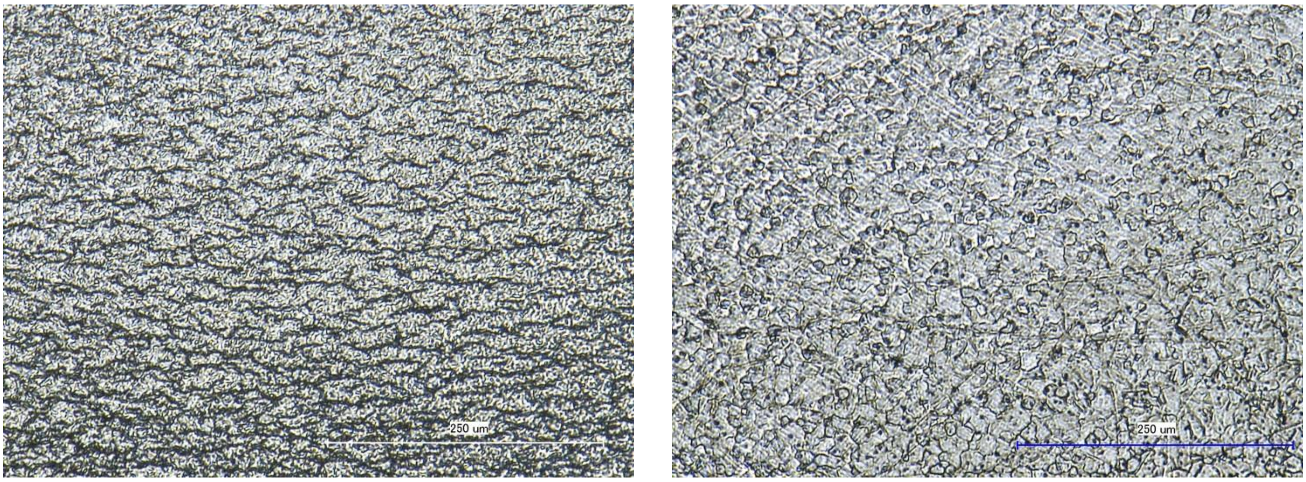


Figure 5 Deflection to fracture as a function of hydrogen concentration. Black, orange and red dots correspond to samples having experienced hydrogenation temperature of 550°, 650 ° and 750 °, respectively. The solid line is a guide for the eye.

The different colours on the graph of Fig.5 indicate the temperature at which the sample was hydrogenated. This may affect the hydrides' orientation at the Zr4 cladding: namely, the higher the hydrogenation temperature the more random the orientation of the hydrides. The zirconium hydrides orientation can be investigated with the use of metallography. Fig.6 shows pictures taken for Zr4 samples hydrogenated at temperatures of 550°C (Fig.6a) and 750°C (Fig.6b). At 550°C mainly circumferential hydrides are formed, whereas randomly oriented hydrides are observed in the sample hydrogenated at the higher temperatures.



(a) (b)

Figure 6 Metallography images illustrating the hydride orientation in Zr4 cladding samples hydrogenated at different temperatures: a) circumferential orientation prevails at 550 °C; b) randomly oriented hydrides formed at 750° C.

Conclusions

A 3-point bending device for investigating the mechanical properties of spent nuclear fuel rods was successfully tested. The device was calibrated using hydrogenated Zr4 cladding filled with alumina pellets and pressurised to 40 bar. Applied load, deflection and internal pressure of the sample are measured up to sample failure. The results showed the influence of the hydrogen content in the cladding on the response of the sample to mechanical loading. At very low hydrogen content the material preserves its ductility. An essentially linear correlation between the deflection (or absorbed energy) and rupture was observed for hydrogen content in the range up to ~700 ppm. For very high concentrations, the segment failure is independent from the hydrogen content.

The performance of the setup is very promising to achieve several objectives. On one hand empirical formulas (e.g. for the critical absorbed energy to fracture) can be derived for characterising mechanical properties of spent fuel rods with different burnup, fuel composition and irradiation history. Such data is essential for simulation purposes, when theoretical models have to be validated against experimental data. On the other hand, the results describe the response of the spent fuel rod to mechanical solicitations, which is crucial for licensing purposes of e.g. transportation of dry/storage casks, handling operations of spent fuel assemblies in hot-cell environment, etc. (especially after storage).

Spent nuclear fuel rods are expected to show somewhat different behaviour than the unirradiated hydrogenated Zr4 with alumina pellets. Therefore, it is not safe to draw any conclusion only from the cold test campaign which can be valid to describe the behaviour of SNF. The new setup will be installed in hot cell and used for a hot test campaign to be carried out on PWR spent fuel rod segments.

The bending setup will become part of a suite of experimental tools aimed at characterizing mechanical properties and behaviour of spent fuel under quasi-static and dynamic loading conditions

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