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A Methodology for the Evaluation of Fuel Rod Failures under Transportation Accidents

Joseph Y. R. Rashid and Albert J. Machiels

ANATECH, San Diego and EPRI, Palo Alto, USA

Abstract

Recent studies on long-term behavior of high-burnup spent fuel have shown that under normal conditions of storage, challenges to cladding integrity from various postulated damage mechanisms, such as delayed hydride cracking, stress-corrosion cracking and long-term creep, would not lead to any significant safety concerns [1,2] during dry storage, and regulatory rules have subsequently been established to ensure that a compatible level of safety is maintained [3]. However, similar safety assurances for spent fuel transportation have not yet been developed, and further studies are currently being conducted to evaluate the conditions under which transportation-related safety issues can be resolved. One of the issues presently under evaluation is the ability and the extent of the fuel assemblies to maintain non-reconfigured geometry during transportation accidents. This evaluation may determine whether, or not, the shielding, confinement, and criticality safety evaluations can be performed assuming initial fuel assembly geometries.

The degree to which spent fuel re-configuration could occur during a transportation accident would depend to a large degree on the number of fuel rod failures and the type and geometry of the failure modes. Such information can only be developed analytically, as there is no direct experimental data that can provide guidance on the level of damage that can be expected. To this end, the paper focuses on the development of a modeling and analysis methodology that deals with this general problem on a generic basis. First consideration is given to defining accident loading that is equivalent to the bounding, although analytically intractable, hypothetical transportation accident of a 9-meter drop onto essentially unyielding surface, which is effectively a condition for impact-limiters design. Second, an analytically robust material constitutive model, an essential element in a successful structural analysis, is required. A material behavior model, with embedded failure criteria, for cladding containing various concentrations of circumferentially and radially oriented hydrides has been developed and implemented in a finite element code. The characterization of hydrides-dependent properties of high-burnup fuel cladding is the main feature of this constitutive model. The third element in the overall process is to utilize this material model and its host finite element code in the structural analysis of a transportation cask subjected to bounding accident loading to calculate fuel rod failures and failure mode configurations. This requires detailed modeling of the transport cask and its internal structure, which include canister, basket, fuel assembly grids and fuel rods. The overall methodology is described in the paper.

1. Introduction

Spent fuel with burnup levels in excess of 45 GWd/MtU is designated as “high burnup” in the context of US regulatory safety reviews pertaining to dry storage and transportation applications. High burnup effects are mostly associated with the role of hydrogen in modifying cladding mechanical and fracture properties. The total hydrogen content in zirconium-based claddings may consist of three components:

1. Hydrogen in solid solution in the zirconium matrix;
2. Hydrogen trapped into irradiation defects; and
3. Hydrogen in the form of solid zirconium hydrides.

The distribution of hydrogen between solid solution (Item 1) and zirconium hydride (Item 3) depends on temperature and whether the cladding is being heated or cooled [4]. The trapped hydrogen (Item 2) plays a role only to the extent that irradiation defects are created or annealed. For PWR fuel rods, hydrides generally appear as platelets tens of micrometers in length, 1-2 micrometers wide, and randomly spaced azimuthally, when viewed in the cladding cross-sectional plane, The hydrides are mostly oriented circumferentially and their radial distribution varies from a very dense, almost solid, hydride rim at the metal/oxide interface, to a relatively sparse spacing at the cladding inner surface.

When the fuel is discharged to the spent-fuel pool, where the average cladding temperature is maintained below 50°C for several years, most of the hydrogen in solid solution prior to discharge precipitates to form zirconium hydrides. When high burnup spent fuel is removed from wet storage and placed in dry storage casks, the cladding will experience a rise in temperature, which will lead to the dissolution of a fraction of the hydrides present at pool temperature. This effectively re-sets the conditions for the process of hydrides precipitation in the cladding during subsequent slow cooling in dry storage, potentially leading to the formation of radial hydrides superimposed on the initial circumferential hydride structure.

Minimizing the conditions for the formation of radial hydrides through operational restrictions is the primary objective of Interim Staff Guidance –11 (ISG-11), Revision 3 [3], which limit the calculated peak cladding temperature to 400°C, with corresponding limitation on the number of thermal cycles, during cask loading, drying, and inerting.

Radial hydrides, superimposed on the original circumferential hydride structure, is the principal damage mechanism to consider under transportation accidents, and the degree to which this damage mechanism can contribute to fuel reconfiguration is the primary focus of the methodology described in this paper. This methodology consists of five major elements:

1. Definition of an analytically tractable cask-impact loading that simulates the hypothetical transportation accident;
2. Definition of fuel rod failure modes and corresponding failure measures anticipated under the accident conditions in (1);
3. Characterization of the evolution of the cladding hydride structure during dry storage, which forms the cladding initial conditions for transportation;
4. Development of a material constitutive model and failure-mode-specific failure measures for cladding with the hydride structure in (3); and
5. Development of a structural analysis procedure using elements (1), (2), (3) and (4) to determine the extent to which spent fuel re-configuration can occur as a result of an accidental drop during handling or transportation.

2. Definition of Spent Fuel Cask Impact Loading

The design basis loading for spent fuel shipping casks is prescribed by the regulatory definition of a hypothetical transportation accident, namely, a 9-meter drop of a fully loaded cask onto an essentially unyielding surface. This definition is effectively a condition for the design of cask impact limiters, for which a variety of designs exists in the industry, ranging from crushable foam to wood and metal honeycomb construction. Each design is unique and is characterized by vendor-proprietary force-displacement curves determined from crush tests that simulate end, side and CGOC (center of gravity over corner) cask-drop orientations. These force-displacement curves, which are essentially models that transform the analytically intractable unyielding surface to a deformable target, are used as the reaction force history to the 9-meter free-fall kinetic energy to calculate cask maximum deceleration (g-loading). The goal is to design impact limiters that limit the g-loading to within the acceptance criteria for the fuel containment boundary, namely the cask closure, as the primary requirement. However, the emergence of the high burnup issue has resulted in paying more attention to fuel behavior, which places greater demands on the analysis process than has been considered for licensing in the past. More detailed modeling and analysis are needed that allows accurate determination of the fuel rods failure configuration. Consequently, it is necessary to perform such calculations without relying on case-specific or proprietary impact-limiter design information. This requires replacing the design basis event, namely, the 9-meter drop onto an unyielding surface, by an equivalent event that does not rely on proprietary information. This equivalence is proposed in the form of a bare-cask drop, from any practical height, onto a reinforced concrete slab on grade designed to meet the seismic requirements of a spent fuel storage pad.

Using the results of the EPRI target hardness study and supporting drop tests sponsored by EPRI and the USNRC [5], it is shown that the maximum steady deceleration resulting from the drop of a bare cask onto a target consisting of a seismically designed reinforced concrete cask-storage pad is bounded as depicted in Figure 1. Reference [5] describes the target hardness model, which calculates the maximum steady deceleration as function of target design parameters and cask drop orientation. As can be seen from the figure, the steady deceleration asymptotically approaches a maximum value 83 g at a drop height in the range of 2.5-3 meters. The steady deceleration is defined from the impulse momentum, as the area under the deceleration-time curve for the initial pulse, divided by the duration of the pulse. The significance of the steady deceleration in the present context is that, when used in an incremental static analysis procedure, which is simpler than the dynamic time history analysis, it bounds the dynamic analysis results.

The merits of this approach are: first, a seismically designed spent fuel storage pad represents a conservative substitute for realistic targets that are likely to be encountered during transportation; second, as a generic approach it can serve as an independent validation of case-specific analyses, which would greatly simplify the regulatory review process; third, it makes the process analytically robust by allowing parametric variations from which probabilistic assessment of consequences can be made. This substitute definition of a hypothetical transportation accident is integrated with the spent fuel cask in a detailed finite element analysis procedure, as will be described in a later section.

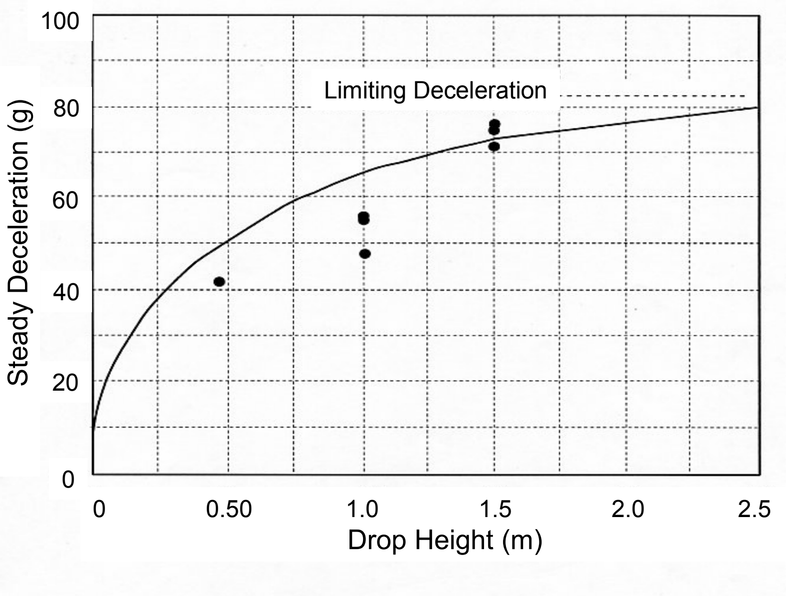


Figure 1 – Model Prediction of Steady Deceleration vs. Drop Height Compared to End Drop Tests of BNFL's 64 metric ton Metal Cask Conducted by BNFL for EPRI/Industry and USNRC, Re. [5].

3. Definition of fuel rod failure modes and failure measures

The degree to which spent fuel reconfiguration can occur during the design basis accident described above depends on the geometry of the possible failure modes. A detailed analysis of fuel failures under hypothetical transportation accidents, conducted by Sandia National Laboratories (SNL) as part of source term study [6], predicts three possible failure modes, which are depicted in Figure 2. Failure Mode-I is initiated under bending type deformations, and can potentially extend to failure Mode-II. Both of these modes do not engage radial hydrides, in contrast to failure Mode-III, which, because of the effect of radial hydrides, is likely to dominate the evolution of cladding failure during the accident. To enable the prediction of potential fuel reconfiguration, the three failure measures shown in Figure 2, are treated as constitutive properties in the material model, rather than failure criteria that are applied à posteriori to the calculated response. Failure measures ε_f and K_{IC} are, respectively, total elongation in the axial direction and fracture toughness for a guillotine type fracture; the CSED is the critical strain energy density, which is the area under the stress-strain curve determined from mechanical property tests.

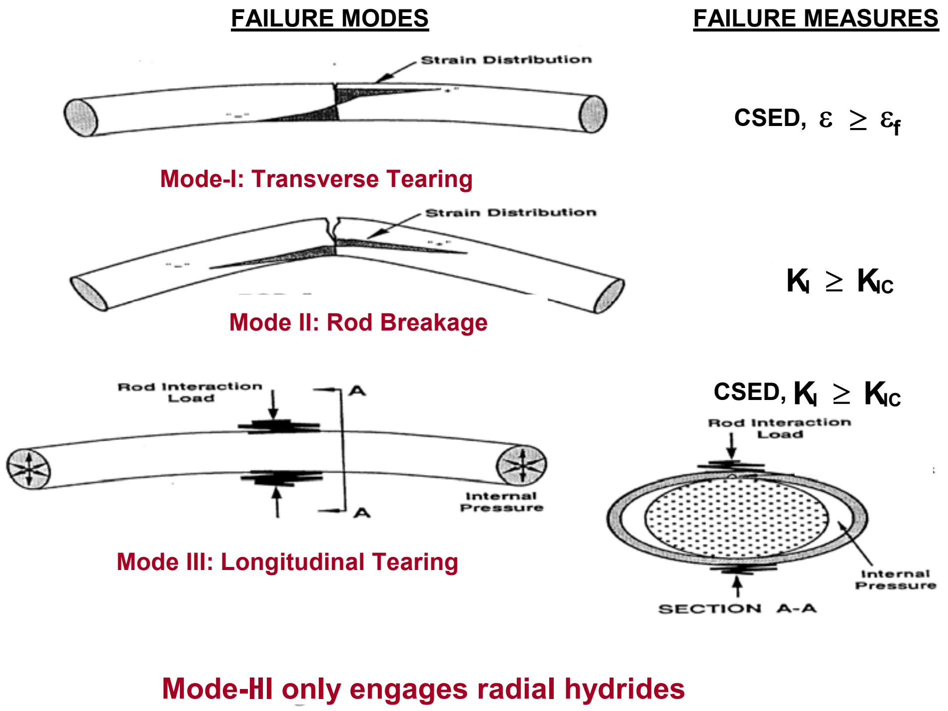
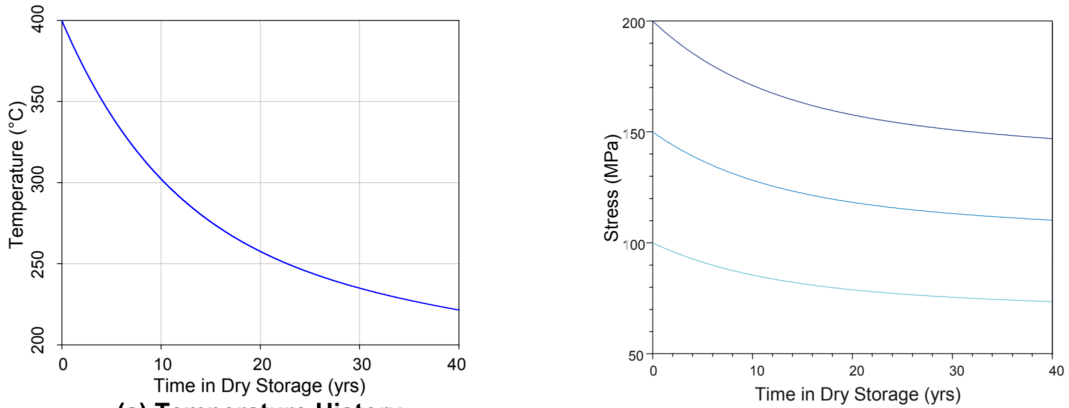


Figure 2 – Failure Modes and Failure Measures Considered in the Response Analysis, Based on the SNL Study, Ref. [6].

4. Evolution of Cladding Hydride Structure in Dry Storage

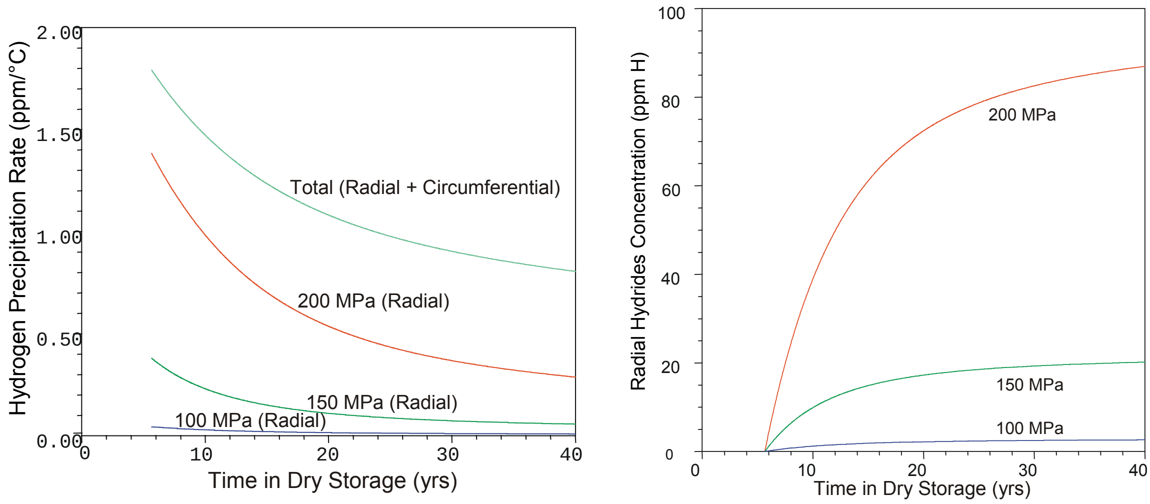
The starting point for the development of an analysis methodology to determine spent fuel failure configuration within a shipping cask subjected to impact forces in a transportation accident is to define the end-of-storage hydride structure in the cladding, which constitutes the initial condition for transportation. Considering high-burnup spent fuel at the end of dry storage licensing period as the limiting case, the cladding hydride structure may consist of mixed (circumferential and radial) hydrides, at concentration levels determined by several factors, namely, the hydrogen concentration at time of discharge from the reactor, the cladding temperature history from initial placement in dry storage, and the fuel rod gas pressure. Based on Canadian work [7,8], a hydride precipitation model has been developed [9], which describes the evolution of the hydride structure during dry storage. The fundamental attribute of this model is the calculation of radial hydride precipitation rate, in terms of ppm hydrogen per °C, as function of the hoop stress history. Knowing the temperature and stress histories, the time integration of the precipitation rate gives the amount of hydrogen precipitating as radial or circumferential hydrides at any time during storage. Typical results of this model are depicted in Figure 3. Figures 3a and 3b show the temperature and stress histories, respectively, for a 60-GWd/MtU, 8.5-year cooled fuel assembly conforming to the ISG-11 temperature limit. Figures 3c and 3d show, respectively, the hydride precipitation rate and evolution of radial hydrides concentration for the three hoop stress histories in Figure 3b. The initial stress values in Figure 3b are selected to cover the stress range expected in high-burnup fuel, with 100-150 MPa being the dominant range. The 200-MPa stress is also included for illustration.

As can be seen in Figure 3b and c, it would take nearly six years in dry storage before the super-saturation limit state is reached before the hydrogen in solid solution begins to precipitate. For an initial 200-MPa hoop stress, the radial hydride concentration at the end of a 40-year dry storage period would not exceed 90 ppm, Figure 3d; however, the average cladding temperature then would be ~220°C, which is in the upper range of the brittle-ductile transition for hydrides [10]. The next step in the present methodology, to be described next, is to develop a material constitutive model that describes cladding behavior containing a hydride structure similar to that depicted in Figure 3.



(a) Temperature History

(b) Fuel Rod Hoop Stress



(c) Hydrogen Precipitation Rate

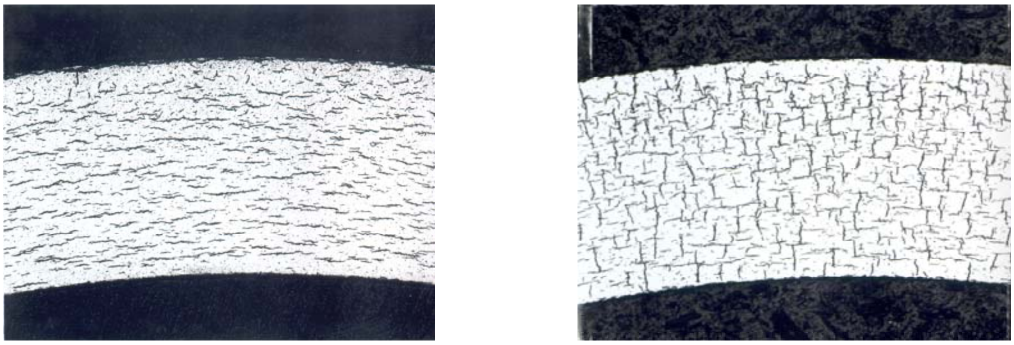
(d) Radial Hydrides Concentration

Figure 3 – Model Prediction of Hydrides Evolution During Dry Storage – Burnup: 60 GWd/MTU; Cooling Time: 8.5 years; Initial temperature: 400°C; Initial hoop stress: as shown.

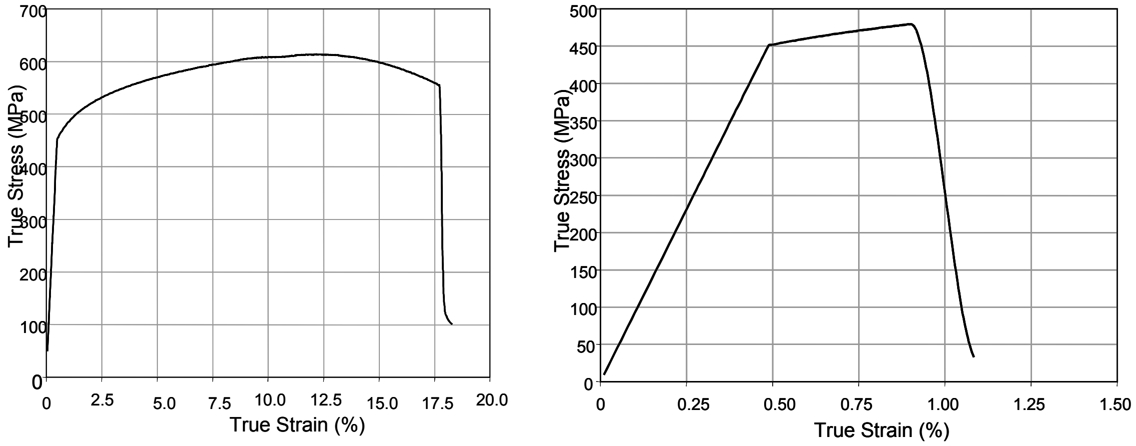
5. Material Model for Cladding with Mixed Hydride Structure

A material constitutive model in which material failure measures are embedded as constitutive properties has been developed for cladding with mixed hydride structures of the types depicted in Figures 4a and 4b [11]. This material model interfaces with the hydride precipitation model discussed in the preceding section. The cladding is modeled as a three-phase mixture composite consisting of a metal matrix in which circumferential and/or radial hydrides are embedded. The hydride phases interact with the Zircaloy metal phase through rigorously enforced interface constraints that satisfy the necessary stress-equilibrium equations and strain-compatibility relations between the phases.

An essential feature of the model is a damage formulation that models the interaction between the cladding response and the cladding failure modes. This unique feature of the model makes it possible for fuel reconfiguration, to the degree it can develop, to evolve as part of the response during the loading event being analyzed, in contrast with conventional methods in which the analysis is performed first followed by à posteriori application of failure criteria.



(a) As Hydrided (220 ppm) **(b) 27% Radial Hydrides at R.T.**



(c) Axial Stress-Strain Response **(d) Azimuthal Stress-Strain Response**

Figure 4 – Model Simulation of Stress-Strain Response at 25°C of Specimen with Mixed Hydride Structure

The starting point for the model is mechanical properties data for the metal and hydride phases isolated from each other, i.e., circumferential and radial δ-hydride phases and irradiated Zircaloy phase. Using the individual properties of the three phases, the model produces a set of stress-strain relations in a general three-dimensional framework, which are used in formulating the governing system of equations in a general-purpose finite element code. Although the model's database is evolving, sufficient model benchmarking and validation has been achieved to permit its use in the analysis of spent fuel transportation casks subjected to impact loading. An example of the model's capabilities is presented in Figure 4, which shows a micrograph of as-hydrided specimen with ~220 ppm hydrogen (a), and after creating radial hydrides (b), by cooling from 300°C under a hoop stress of 225 MPa. The testing laboratory is INER, Taiwan, and the results are reported in Yagnik, et al. [12]. By calculation, the hydrogen content of the radial hydrides is approximately 70 ppm, which leaves 150 ppm in circumferential hydrides. The stress-strain response is not available, but total elongation data for specimen (b) with mixed hydrides, Ref. [12], is ~ 17.5% in axial tension, and 1.5% in the hoop direction, the latter being the property most affected by radial hydrides. The model's simulation of the specimen's response in the axial and azimuthal directions is shown in Figures 4c and 4d, respectively. As can be seen, the effects of radial hydrides on the axial response is effectively nil, whereas the hoop ductility is significantly reduced.

6. Structural Analysis Procedure for Fuel Re-configuration

Fuel-assembly/fuel-rod response and consequent fuel rod failure during a cask drop event is dependent upon the orientation of the cask as it impacts the target surface. The three possible cask orientations normally considered are: end drop, side drop, and a CGOC drop with slap down. The SNL source term study [6], cited earlier, identified the side drop as the configuration that produced the highest failure probabilities, with failure Mode-III having the highest failure frequency. Although that study utilized cladding properties for burnup in the range of 25-35 GWd/MTU, for both BWR and PWR, which was the typical burnup level at that time, the relative ranking of the failure modes would not be altered in high burnup fuel. Moreover, because of the further impact of radial hydrides, it can be safely assumed that the side drop would be the governing drop orientation. Figure 5 shows a finite element model for a quarter-symmetry model of a transportation cask on a 1-m thick spent fuel storage pad. This figure shows the degree of details used in performing the structural analysis required for the evaluation of fuel reconfiguration.

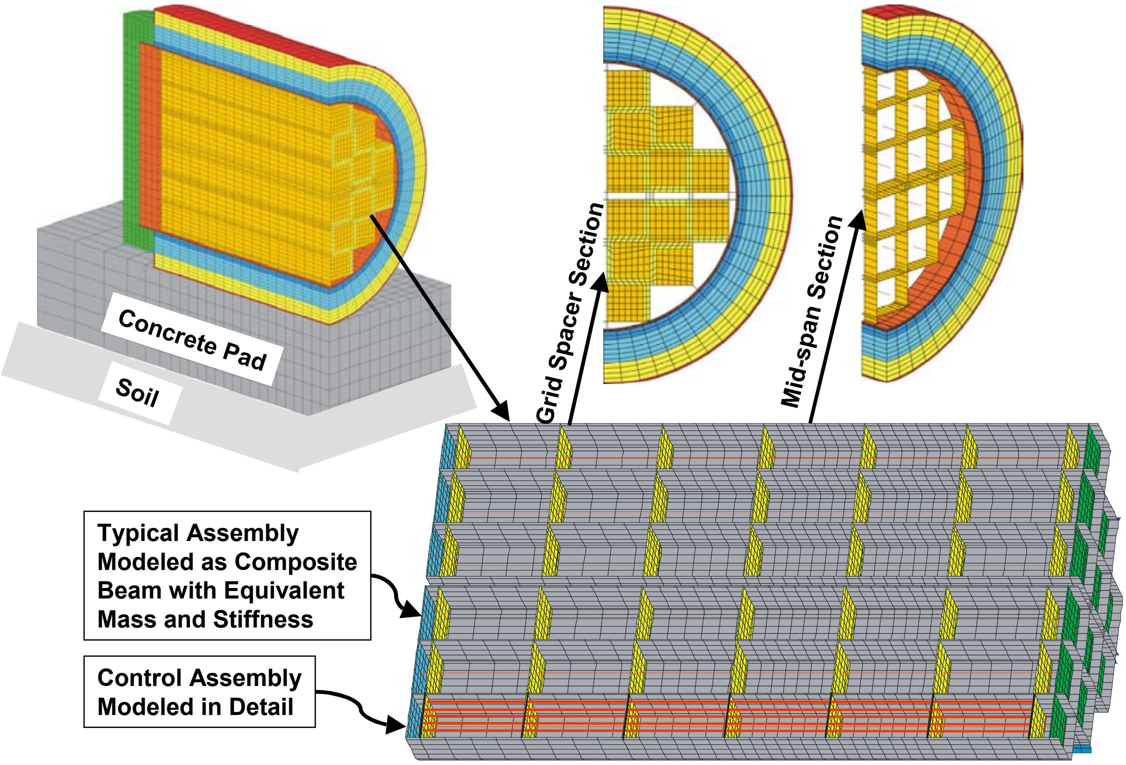


Figure 5 – Finite Element Model for Hypothetical Transportation Accident Analysis

The global model in Figure 5 is analyzed to obtain rod-to-rod force time histories for the fuel rods in the control assembly, using a finite element code equipped with the concrete/soil-foundation analysis methodology employed in the EPRI target hardness study [5]. Consistently with that methodology, the velocity of free fall from the bounding height in Figure 1 is used as the cask impact velocity onto the concrete pad and underlying soil. The emphasis in this analysis is on the load transfer between the cask, the canister, the basket structure and the fuel rods, with the basket structure and grid spacers in the control assembly as the only components subject to buckling or failure. No fuel rod failures would be predicted in this global analysis; therefore, the usual high-burnup stress-strain properties are used for the cladding. The rod-to-rod force time histories, which vary depending upon the rod's position in the control assembly, are applied to a 3D finite element model of a single fuel rod, with a high degree of detail in the cross section to capture the effects of the hydrides distribution. Time history analysis, utilizing the hydride precipitation model and the material constitutive model described in the preceding sections, is carried out to determine fuel rod failure configuration. The single-rod analysis is repeated for a sufficient number of rods in the control assembly to enable the construction of a complete picture of fuel rods failure-modes geometry, frequency and distribution. If significant reconfiguration of the control assembly is predicted, the entire analysis procedure is repeated with the control assembly positioned in a different cell in the basket structure until the analysis shows benign response or can be extrapolated to the remaining assemblies.

7. Conclusion

Evaluation of fuel rods failure configuration in a shipping cask subjected to a hypothetical transportation accident is a complex process that engages a number of different technical disciplines for which new phenomenological understanding and descriptive behavioral models need to be developed before a quantitative evaluation can be attempted. A methodology for such a quantitative evaluation is described in the paper, making use of new developments [9, 11] in describing cladding hydride structure and its potential effects on cladding failure regimes, and building on two significantly relevant methodologies: the SNL source term study [6] and the EPRI target hardness study [5]. By combining these various elements in a cohesive interacting system of modeling and analysis, the process of spent fuel failure evaluation becomes analytically tractable, although the work effort may be significant.

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