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Uncertainties in seismic design of free-standing HDSFS racks

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I. INTRODUCTION

High Density Spent Fuel Storage (HDSFS) racks are structures designed to hold nuclear spent fuel assemblies removed from the nuclear power reactor after having been irradiated. They are used in the first step of the waste management process, during the wet storage.

The underwater seismic response of HDSFS racks is a troubling safety issue. Since they are 12 m submerged free standing multi-body structures loaded with radioactive fuel, their design remains as complex as crucial [1] [2]. The design deals with a Fluid-Structure Interaction (FSI) problem, a transient dynamic response and a very highly nonlinear behaviour. Several cost-effective industrial approaches have been used in these calculations to date, but some dispersion of results still exists. Therefore, the regulatory authorities are requiring an evaluation of the uncertainties in the methodology.

Equipos Nucleares, S.A. (ENSA) is a worldwide expert in racks design and construction [3] and has recently launched a research project to improve the understanding of the phenomena. The latter is funded by the European Comision[1] and aimed to identify, evaluate and reduce the uncertainties involved in the calculations. In this paper, the state of the art and the current sources of uncertainty are discussed.

II. CONTEXT AND DIFFICULTIES

A. Characteristics

Some typical features of HDSFS Racks are outlined below:

- unique and singular structure (interlocking cell matrix),
- tailored dimensions adapted to the Spent Fuel Pool,
- made of structural stainless steel and neutron-absorbing materials,
- radioactive ambient with restricted access avoiding any ground fixation,
- free standing structure resting on the floor of the pool,
- multi-body analysis combining several racks with multiple fuel assemblies rattling inside its storage cells,
- submerged conditions (under 12m water head),
- nuclear regulation imposing the highest seismic requirements.

B. Nuclear Authorities requirements

Nuclear authorities are mainly concerned about rack displacements, rack rocking and maximum forces on supports, but only some basic guidelines have been provided as design criteria. Licensing acceptance criteria depend on codes and standards specific for each country. For instance, the USNRC refers to the USNRC 1981 and ASME code 1998 [4].

Become aware of the degree of uncertainty brought by the analysis methodology is essential to this approval and licensing process. To take up this challenge, both deterministic and statistical approaches are allowed, but the designer's analysis methodology must be submitted for approval.

C. Description of the dynamic problem

The seismic design faces the main three following complex physical phenomena [5]:

1) Fluid-Structure Interaction. The presence of water determines the dynamic response of the racks and fuel assemblies. Inertial effects derived from the water acceleration lead to coupling forces between structures.

2) Highly nonlinear behaviour. the large displacements and changing-status contacts create singularities, up to the point that the frequency of the rack decreases when the excitation increases due to the sliding on the pool floor [6]. The sliding, rocking and lift-off of racks affects the thickness of initial water gaps and may cause the impact of fuel assemblies on the storage cell as well as between racks.

3) Transient Dynamic response. Because of the inherent nonlinearities, the response of the rack system does not satisfy the superposition principle. The 3D displacements and rotations should be analysed by the direct step-by-step integration of the dynamic equation throughout the entire seismic event. The basic equation of motion is given by:

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{F(t)\} \qquad (1)$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the structural system respectively and $\{u(t)\}$,$\{\mathrm{d}u(t)/\mathrm{d}t\}$ and $\{\mathrm{d}^2u(t)/dt^2\}$ are vectors containing the translational and rotational degrees of freedom of the structure and their respective velocities and accelerations. $\{F(t)\}$ is the time-varying vector of forces applied at each of the degrees of freedom.

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III. CURRENT SOURCES OF UNCERTAINTY

Industry is currently using available commercial computer-aided Finite Element Analysis software to solve the design problem in a cost-effective way. There is a significant degree of uncertainty associated to the variables defining the scenario in Section II, and some discrepancies between models and reality remain [7]. The sources of uncertainty have been inventoried and classified into seven categories:

A. Input data

Precise input data are rarely if ever available. In general, they already contain uncertain information, including sampling errors, modelling errors and instrument errors, which may preclude the possibility of knowing the input data exactly.

This concern is highlighted in the racks seismic analysis where input data are not deterministic but highly stochastic. For instance, friction coefficient between rack supports and pool liner, thickness of water gaps and location of each rack in the pool, earthquake design accelerogram, fuel mass and loading configuration among others, are stochastic variables.

An efficient representation of the inputs facilitates accurate estimations of random responses' statistics. It is then worthwhile to gather an understanding on how uncertainties propagate from the input data to the output results when real conditions differ from those reflected by the model inputs.

B. Conceptual and mathematical model

Modelling is the idealization process by which the real system under study is assimilated to a manageable simplification. Hence, models are imperfect abstractions of reality built to provide answers to the asked analysis questions. In some manner, they describe our belief about the behaviour which is then translated into the language of mathematics (Fig.1). The final mathematical formulation includes the complete specification of all partial differential equations (PDEs), the auxiliary conditions, the boundary conditions, and the initial conditions for the system.

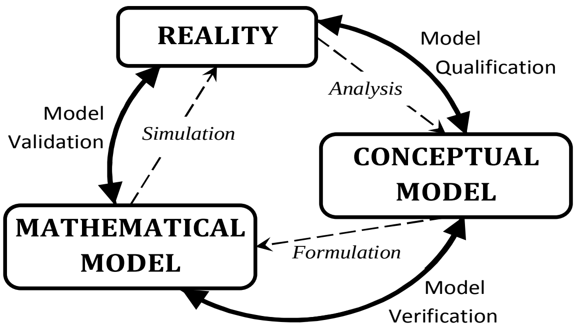

Figure 1. Conceptual and mathematical modelling process Adapted from [8] and [9]

The Engineer should be familiar with the advantages, disadvantages, accuracy and range of applicability of his model and, be able to run it within a reasonable amount of time. Hence, models are conditioned by the parameters of study and may be significantly different for a static or a dynamic analysis. For example, seismic analysis of racks systems are so complex that it is necessary to carry out many simplifications to reduce the computational effort derived from the transient dynamic calculations [10].

In seismic analysis, racks are usually analysed through a 3D stick model built with simple wired elastic beams. In this 'defeatured' model, the thin-walled cellular structure is represented through a unique beam, the fuel assemblies are usually grouped in a vertical rigid body at the corresponding centre of masses, and the base plate and rack feet are shaped as rigid bodies. In order to preserve the appropriate dynamic properties, the stiffness and mass distribution are set on the basis of another detailed model. [11].

In such an analysis, special attention should be given to the assumptions related to variable boundary conditions, the nonlinearities, the fluid-structure interaction, the fuel assemblies' interactions, and the load input. For example, it has been recommended to use the acceleration-time history rather than the displacement-time history as a seismic input [12]. Furthermore, it is generally assumed that fuel assemblies move in unison because any variation from this conservatively assumption is difficult to justify.

C. Finite Element Methods

Ad hoc simple models symbolise the first step, but they are not necessarily easy to solve. Such models may have an infinite number of degrees of freedom and they often involve coupled differential equations in the space-time subjected to interface and/or boundary conditions. When analytical solutions are difficult to be found or directly do not exist, the continuous mathematical model is generally discretized into a multiple components of simple geometry that can be addressed through computational analysis.

The basic concept in the so-called physical finite element method is the subdivision of the mathematical model into disjoint (non-overlapping) finite elements. The collection of all finite elements encompassed in the model is finally assembled according to their assumed behaviour by coupling displacement and rotations of concatenated nodes and by creating solid contacts or fluid connections (Fig. 2). When appropriate connexions are performed, the response of the discrete model is considered to be a reasonable approximation to that of the continuous mathematical model.

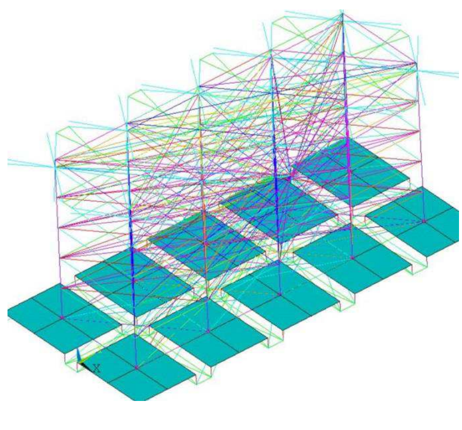

Figure 2. Mathematical finite element model representing 10 racks and their multiple interconnexions for seismic assesment purpose

The finite element method is a pure mathematical conversion and does not affect the continuous physics of Eulerian and Lagrangian formulations. However, it deals with questions such as the consistency of the discrete equations with the PDEs, the numerical method stability, the mathematical singularities approximations and the differences in zones of influence between the continuum and discrete systems. Irrespective of the accuracy in the numerical calculations, the resulting convergence and error characteristics of the finite element equations can be determined through the analysis of the ordinary and partial differential equations created during the Taylor series expansions.

As outlined above, the discretisation process arises an inherent error. Its importance depends on the number of considered elements and the shape of the mesh. Generally speaking, the finer the mesh, the smaller the discretization error, but computational time increases. Beyond a certain level of discretization, a finer mesh may not necessarily result in greater accuracy. The engineer should specify a good combination of mesh density and element order. Great care is needed in areas of rapidly changing stresses, e.g. rack feet.

D. 3D large displacement analysis

During an earthquake event, the free-standing racks suffer large displacements, namely uplift, bend, slide, twist, rotate and eventually impact on the adjacent units or pool wall.

The analysis of these nonlinear large displacements becomes an intricate task as soon as finite elements with rotational degrees of freedom in all directions are considered. The fundamental reason for these difficulties lies in the non-commutativity of successive finite effects. Unless the 3D seismic components are applied simultaneously, nonlinear displacements may not be accurately predicted.

This issue poses a great challenge in the mathematical computation. There is no analytical equation of motion throughout the physical domain so it is necessary to resort to incremental equilibrium equations. The iterative incremental formulation is written in matrix form and so easily computable in along the moving interface [13]. Moreover, the incremental formulation allows the straightforward inclusion of constitutive relationships which are depending on the physics interface.

Different approaches based on continuum mechanics principles are encompassed within the incremental formulation. The conceptual difference is the reference configuration that is used for tracking the boundary conditions and the linearization of the incremental equations of motion [14]. In the Lagrange formulation, the initial configuration is used as reference whereas in the Eulerian formulation the reference configuration corresponds to the last calculated configuration

It is noted that the choice of the algorithm determines the relationship between the deforming continuum and the computational mesh, and thus determines the capacity to deal with large displacements and mobile boundaries.

E. Contact conditions

A contact creates a high discontinuity. The analysis of this “changing-status” of nonlinearity requires significant computer resources. Several formulations have been developed to achieve compatibility at the contact surface and satisfy the appropriate physical and mathematical boundary conditions: Normal Lagrange, augmented Lagrange, pure penalty, multi-point constraint, etc.

The engineer should understand the physics of the contact problem and take the time to set up an efficient formulation with the adequate convergence rate and free from ill-conditioning the stiffness matrices. These considerations are highlighted in racks analysis where contacts represent the main source of nonlinearities. Boundary conditions vary with time depending on the displacement and deformation of the racks. Initial contacts points can be cleared (e.g. uplifted support feet), and new ones can appear at each instant (e.g. physical contact between solids nearby such as the pool wall or neighboring racks). This issue brings a double source of nonlinearities both in forces and in displacements.

An accurate representation of the impact is extremely difficult. Despite its conservatism has not been showed, no-interpenetration conditions are arbitrarily enforced between independent racks. The resulting impact force is usually modeled by means of nonlinear spring elements located inside each physical gap. These elements do not transmit tensile normal forces and its stiffness ranges from zero just before the impact to near infinite when contact occurs.

After the contact event, the two solids may slide relative to each other along the interface. A frictional force opposite to the movement appears at the contact point as a consequence of the normal reaction. The force is often modeled through Coulomb friction elements. Such elements behaves as stiff springs until the force reaches a limiting value equal to the specified friction coefficient times the normal force. This assumption estimates a unique constant friction coefficient and ignores the differences between static and dynamic values. Separate analyses are usually performed to consider upper and lower limits on the friction coefficient in order to consider a maximum sliding case and a maximum rocking case respectively.

F. Fluid-structure Interaction (Hydrodynamic mass)

During a seismic event, racks units and water vibrate. In addition to the buoyancy vertical force, the fluid-structure interaction (FSI) must be considered both for the fuel element inside its channel, and for the racks themselves inside the spent fuel pool. The FSI phenomena are derived from the geometrical relationship in the pool, characterized by flat structures with large surfaces (the area of a rack wall is in the order of 10m2) separated by relatively small water gaps (in the order of 10mm). Racks motion creates a large fluid pressure inside the water gaps that has an important effect on the dynamic behaviour of the complete system, particularly in the eigenfrequencies and damping characteristics.

Ideally the hydrodynamic force should be calculated based on the full 3D turbulent Navier-Stokes equation, but this is difficult even in simple cases. Current analysis assume some simplifications in water behaviour, ignoring fluid damping and sloshing effects, and use the hydrodynamic mass approach treating the water as a virtual extension of the mass structure which represents the dynamic effect of water [15]. Then, Eq. (1) becomes:

$$\left[M + m_{hydro}\right]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = \{F(t)\} \quad (2)$$

where the added matrix [m_{hydro}] is referred to as hydrodynamic mass and represents added mass (diagonal) terms and inertial coupling (off-diagonal) terms to the system mass matrix. This affects the system frequency and couples the motion of the fuel assemblies, rack units and pool walls.

This approach requires the assimilation of water as an acoustic fluid responding to the potential equation (inviscid, irrotational, and incompressible). The potential theory of fluid flow leads directly to a Laplacian equation for the velocity gradient where boundary conditions are given by the velocities of the in-water structures. Hence, the value of hydrodynamic masses should be affected by the wall deformation and gap thickness and their variation with time, but it is generally assumed a constant gap during the whole seismic event.

G. Transient Analysis - Numerical integration

The seismic analysis requires the resolution of a system of equations which involve time-depending variables. Therefore, it is necessary to implement an iterative numerical method to solve the finite element equations of motion at multiple time steps. It should be noted that even if numerical integration is not very sensitive to the round-off errors (resolution in number of digits manipulated by the computer), truncation errors are committed during the series expansions. Hence, the accuracy of the solution depends on the effectiveness of the numerical method to integrate the Ordinary Differential Equation (ODE).

Due to the high nonlinearities present in the racks system, the modal superposition method has to be avoided and the equation of motion must be solved by numerical direct integration. Direct integration methods attempt to satisfy equilibrium with finite precision at discrete points in space and time. The market proposes a huge number of well-developed step by step iterative algorithms (i.e. Range Kutta, Newmark, HTT, alpha-method, etc.) The convergence of these algorithms is never assured, so it is advised to always check the error in the conservation of energy for every solution obtained. Furthermore, the accuracy and stability of the solver directly depend on the time step parameter and on the order of the derivate. However, the higher accuracy of the simulation, the lower becomes the stability field [16].

The engineer should manually choose not only the most appropriate ODEs solver, but also the optimal control parameters such as: time step, numerical damping, etc. Only single-step, implicit, unconditional stable methods seem to be adapted to the step-by step rack seismic analysis.

IV. Conclusions and Future work

The usefulness of any assessment depends on the accuracy and reliability of its output. The uncertainty accumulated all over the outlined stages may affect the final results in an unpredictable way. This propagation of uncertainty plays a highlighted role in transitory analysis, because the results at the end of a calculus step are taken as initial conditions for the following step. In addition, due to the non-linear behaviour real safety margins are extremely difficult to predict because the response is not directly proportional to the input.

Ongoing research is collecting experimental data from a testing campaign using a physical model to assess the current analysis methodology. Further steps seek to provide an evaluation of each identified source of uncertainty inherent to racks, including an error estimates and an error bound.

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