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Division V

NON-LINEAR MODELING OF PWR FUEL ASSEMBLY DYNAMIC BEHAVIOR IN EARTHQUAKE AND LOCA

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ABSTRACT

The justification of fuel assemblies (FA) mechanical integrity under severe Loss Of Coolant Accident (LOCA) or seismic events is based on numerical models, which predict the dynamic response of a row of FAs subjected to external excitation inside the Reactor Pressure Vessel (RPV).

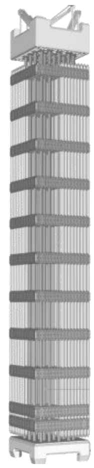
Each FA is a complex structure composed of numerous components and non-linear joints, whose dynamic behaviour is usually approximated by a single linear beam model. This approach is now challenged by the need to address new requirements from the regulators such as accounting for the effect of fuel assembly static distortions in operation, or mixed core configurations. To address these concerns, Framatome has developed an advanced non-linear (NL) dynamic model which allows for an accurate representation of the FA dynamics in terms of oscillating motion, impact stiffness, and fluid-structure interaction. The model is validated against various experimental datasets and its response is evaluated in conditions representative of postulated accident situations.

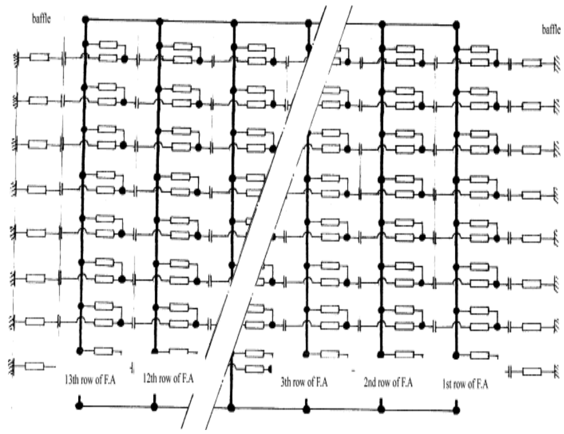
OVERVIEW OF THE REFERENCE MODELING APPROACH

Introduction

Under severe accident conditions such as earthquake or LOCA, the mechanical integrity of the fuel assemblies has to be verified. Due to the FAs being slender, elongated structures (see figure 1.a) positioned next to each other with gaps of about 1 to 2 mm only inside the core, it is expected that the dynamic excitation induced by the accident will result in vibrations of large amplitude of the FAs, and impacts at grid levels.

The analysis of the core response to the dynamic transient is usually performed at the scale of individual rows of FAs, with bi-directional effects judged negligible in general (Queval et al. (1991)). Structural models are used to simulate the dynamic behaviour of the FA row. Such type of model is presented on figure 1.b, and more details with respect to its characteristics are provided in the following sections.





a) b)

Figure 1. a) Fuel assembly overview
and b) Horizontal FEM model of 1×13 fuel assemblies (Yongcheng et al. (2004))

The row model is subjected to time-dependent excitation in the form of motion time-signals which are imposed at the level of the Upper Core Plate, Lower Core Plate (which are represented as horizontal lines connecting FA upper and lower extremities on figure 1.b.) and core baffle. Explicit time transient resolution is used as per Framatome's methodology (see Viallet et al. (2003)) and the results consist mostly in guide-thimble stresses and impact forces at grid levels which are then compared to design criteria.

The objective of this paper is to present an advanced non-linear (NL) dynamic model which allows for an accurate representation of the FA dynamics in terms of oscillating motion, impact stiffness, and fluid-structure interaction. The model is validated against various experimental datasets and its response is evaluated in conditions representative of postulated accident situations.

Review of the reference fuel assembly row model

For practical reasons, historically related to computational time limitations with respect to industrial use, a series of simplifications have been introduced for the modelling of the row response in accident, compared to the actual lateral behaviour of the fuel assemblies. Such type of models, described in Myung (1998), Viallet et al. (2003), and Yongcheng et al. (2004), are referred to as the "reference" models in the following as they are most commonly used in current FA licensing analyses. Their general characteristics are discussed in the next paragraphs.

As represented on figure 1.a, a FA is composed of two sub-structures: the fuel rod bundle, which represents most of the mass, and the cage, composed of the guide-thimbles, grids, and nozzles. Due to the stiffening effect of the spacer grids, the FA behaves mainly like a Timoshenko beam, e.g. its lateral behaviour is driven by shearing deformation modes with the grids remaining mostly parallel to each other. Furthermore, the connections between the fuel rods and the grids, which usually consist in contact points or contact lines, allows for a certain level of mechanical hysteresis. Due to these nonlinearities, the lateral bending stiffness, as well as the natural vibration modes damping and frequency, all vary with oscillation amplitude (Lamorte et al., 2021).

In the reference row model however, the lateral behaviour of the FA is linearized around a vibration amplitude which is judged representative for the whole transient and, in most cases, only a single linear Timoshenko beam is used to represent the complete structure. This approach has been proven well-adapted in the case of earthquake loadings, for which the FA response is mostly driven by that of its first natural vibration mode (Viallet et al. (2003)).

The modelling of impact at grid levels is limited to the use of gapped translational springs simulating the elastic behaviour of the grid (although elastoplastic models can also be considered, as in Painter et al. (2018). Inertial effects induced by the fuel rods motion inside the grids are taken into account thanks to a linear translational spring, often-called "internal" stiffness (as in Myung (1998)).

As the dynamic response of the row under external excitation is affected by the presence of the flowing water, fluid-structure interaction also has to be considered. Inertial couplings between the core barrel and the FAs are accounted for by the means of coupling masses, as described by Rigaudeau et al. (1993). Flow-added damping (Fujita (1990)), which is a first-order contributor to the FA response, is implemented by prescribing to the corresponding vibration modes a reduced damping ratio whose value is derived from full-scale experiments.

DESCRIPTION OF THE ADVANCED NON-LINEAR FUEL ASSEMBLY MODEL

Description of the structural model

The advanced non-linear fuel assembly model is presented on figure 2. It has been developed with the aim to overcome the main limitations of the reference model, which have been described in the previous section.

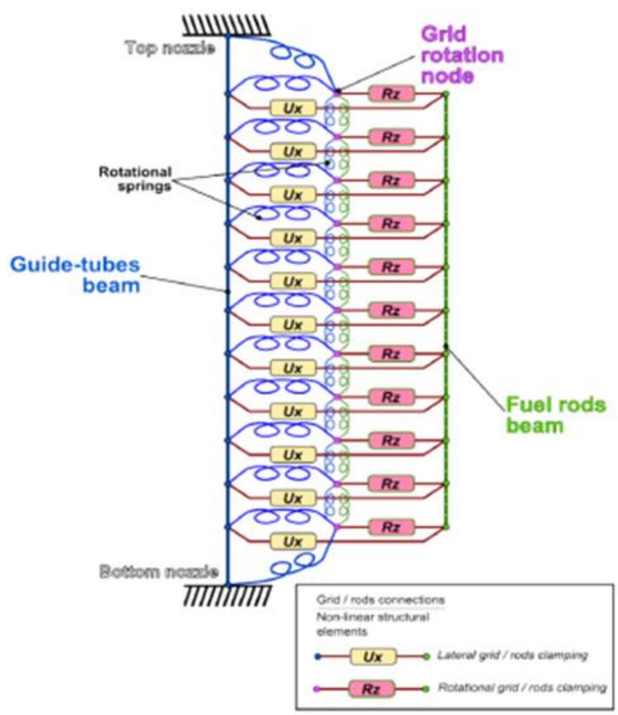


Figure 2: Overview of the advanced non-linear fuel assembly model

The NL model consists in two Euler-Bernouilli beams: one accounts for the guide-tube bundle, and the other for the fuel rod bundle. The characteristics of these two beams are derived directly from the component's individual characteristics (e.g. material properties, and geometry).

Modelling of the connexions with the grids is twofold: rotational clamping stiffnesses are derived from component-scale testing, while the momentum exerted by out-of-axis tubes opposing to the grid rotation is simulated by connecting grid nodes with additional rotational springs, whose stiffness is proportional to the tubes' axial compressibility. In the case of the rod to grid connexion, mechanical hysteresis induced by friction and intermittent loss of contact between the cladding and its supports is accounted for by using non-linear joint models.

With respect to impacts at grids level, the modelling is akin to that of the reference model i.e. either elastic or elastoplastic translational springs with gaps can be used to simulate the grid behaviour, depending on the application. Such impact spring connects the guide thimble beam with the impacting body, e.g. the core baffle or the neighbouring FA. There is no need for an internal stiffness per se, given that the fuel rod bundle bending motion with respect to the grid is explicitly accounted for thanks to the dedicated rod beam. Conversely, a translational linear spring is used to connect the fuel rod beam and the guide thimble beam. It accounts for the compressibility of the rod supports and its stiffness is calibrated accordingly.

Compared to reference row models, the benefits of the proposed approach lie in the fact that no linearization of the FA mechanical behaviour is necessary. Consequently, the numerical values of the parameters of the NL model can be derived from design characteristics such as material properties and geometry, or from component-scale testing without requiring extensive empirical calibration. This is an important point since the experimental data which is usually considered for such calibration step is not obtained in an environment which is representative of the reactor operating conditions. No additional step of extrapolation is required, thus avoiding increased uncertainties with respect to the model capability to predict the actual behaviour of the FA.

The explicit representation of the FA mechanical non-linearities also allows for a more accurate prediction of the dynamic response of the row, which may be required for complex loading cases such as LOCA (whose fast dynamics excite higher vibration modes of the FA). This increased accuracy is also beneficial for cases for which the elastic limit of the grid is exceeded: while in the fully elastic approach the physical quantity of interest is the maximum impact force over the whole row and the whole transient, for elastoplastic grid models the correct prediction of the location of the grids affected by plastic deformation is as important as the prediction of deformation amplitude itself, with respect to subsequent analyses of their consequences on the verification of safety requirements (e.g. RCCA drop).

Modelling of Fluid-Structure Interaction

Different effects related to fluid-structure interactions are considered separately in the advanced non-linear fuel assembly model, namely: inertial couplings, flow-added damping and flow-added stiffness.

The inertial effects induced by the fluid are introduced as non-diagonal terms in the mass matrix (so-called "coupling masses") which connect the degrees of freedom (DoF) of the core barrel nodes with those of the fuel assemblies composing the row. The numerical values of the coupling masses are derived from the mass of water displaced due to the structure motion, with the confinement effect taken into account as a constant amplification factor, consistently with Rigaudeau et al. (1993). This approach is identical to the one used for the reference model described in previous section.

It is assumed that the flow-added stiffness and damping are equivalent to lift forces induced by the fluid flow on the fuel assembly structure, as per Moussou et al. (2017). With the assumption that the FA can be assimilated to a cylinder, the lateral fluid force $F_{lateral}$ is proportional to the lift coefficient, the dynamic pressure of the fluid, the total contact area with the solid, and to the composition of two angles (see figure 3. below):

- A geometrical angle $\frac{dX}{dZ}$ between the axis of the cylinder portion and the flow asymptotic flow direction,
- And an "apparent" angle $\frac{\dot{X}}{V}$ induced by the velocity of the cylinder.

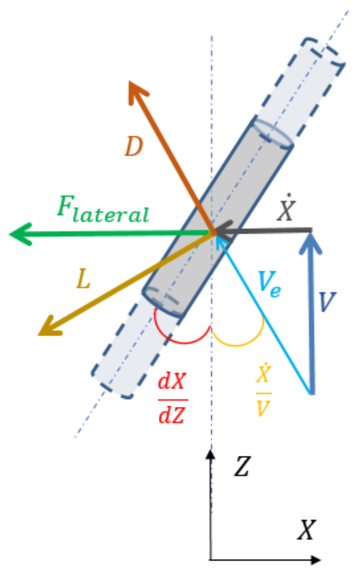


Figure 3: Lift forces acting on the tube bundle

This decomposition allows for separating flow-added stiffness, whose effect is proportional to the FA inclination, and flow-added damping, which is proportional to its velocity. Both effects are then accounted for in the NL model thanks to the introduction of dedicated sets of linear springs and viscous dampers respectively. Finally, the numerical value of the lift coefficient is calibrated empirically to account for both the effect of the tube bundle and that of the grids, based on comparison with reference experimental datasets, as described with more details in the following section.

Compared to reference row models, the benefits of the NL model with respect to fluid-structure interaction comes from the physical basis of the modelling of flow-added damping and stiffness, which makes it possible to account explicitly for the effect of variations of flow velocity or temperature. It must also be emphasized that flow stiffening effects are usually discarded in the case of reference models, hence the higher accuracy of the advanced model.

Finally, one additional advantage of the proposed approach is that it does not require the calibration of damping ratios on a mode-by-mode basis, as the sources of damping are the mechanical non-linearities present in the hysteretic response of the FA and the flow-related effect included in the model. This is of special importance given the high number of nodes of the NL model (which results from the increased number of DoFs) and also considering that modal damping approaches would not be suitable due to the non-linearity of the model itself.

BENCHMARK WITH EXPERIMENTAL DATASETS

Forced vibration tests

In order to verify the capability of the advanced model to predict accurately the dynamic behaviour of the fuel assemblies, a series of sine sweep simulations on a single FA have been performed and their results compared to reference test measurements.

Consistently with the tests, the FA model is representative of the reference 14-feet Framatome fuel assembly design in Begin Of Life condition. Two test configurations are investigated: in air, and in flowing water (5 m/s) with so-called cold conditions (50°C). For each configuration, several vibration amplitudes ranging from 0.5 mm to 10 mm are imposed successively at the level of the 5th grid (G5), to emulate the mechanical loading induced by the actuator used for the tests (as seen on figure 4.a.).

For each simulation, the time-histories of imposed displacement at G5 and corresponding external force are used to derive equivalent modal properties (natural frequency and damping ratio) which are then compared to those derived from the tests.

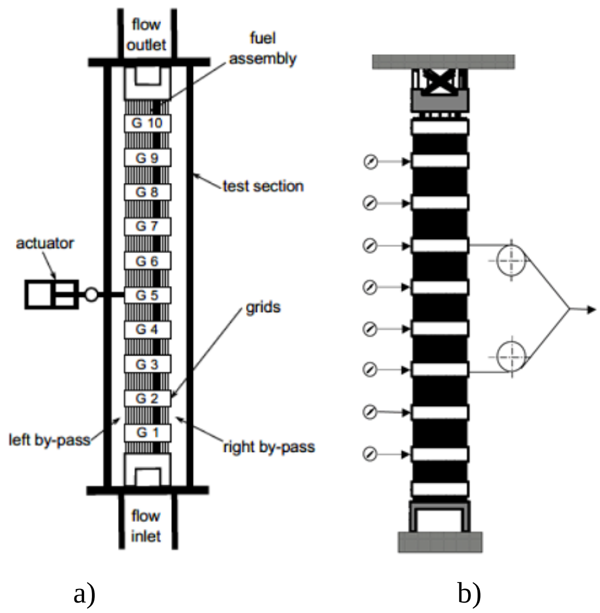


Figure 4: Experimental configurations – a) forced vibrations, b) lateral pluck with impacts

The results are presented on figures 5. and 6. As it can be seen, the simulation results are in good agreement with the tests. The mechanical non-linearities, which are responsible for the variation of natural frequency and damping ratio with vibration amplitude, mainly result from the rod sliding inside the grid cells. Such sliding only occurs when the vibration amplitude is high enough, hence the higher stiffness and lower damping at low amplitude. This effect is well captured by the model.

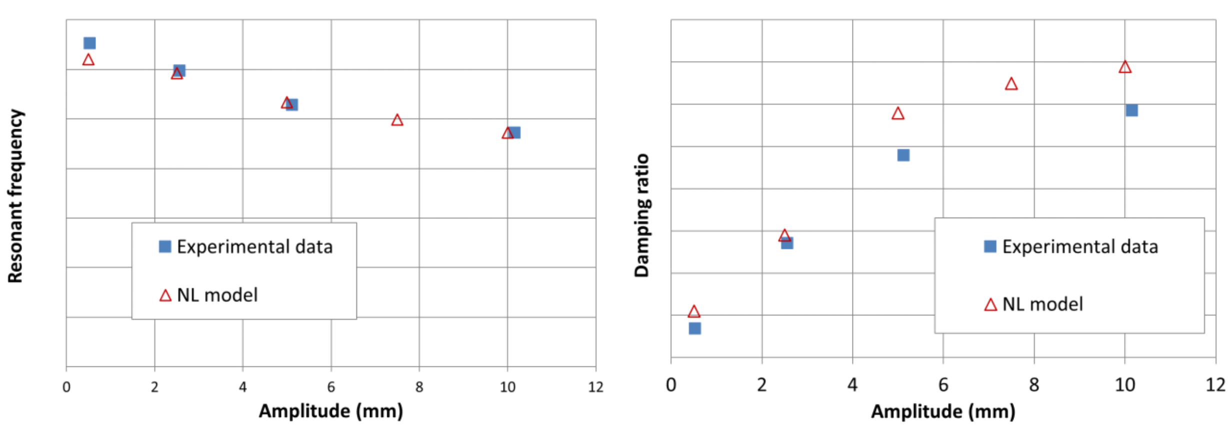


Figure 4: FA vibration in air – 1st resonant frequency (left) and damping ratio (right)

With respect to structural damping, it can be observed from figure 5. that some deviation exists at large amplitude, even though the main trend is correctly predicted. Such deviation is judged acceptable, considering that, in the operating conditions of the reactor, the main contributor to damping is the flowing water. In other words, the appropriate calibration of lift coefficient makes it possible to obtain the targeted value of damping ratio. This is confirmed by the results presented on figure 6. For these simulations, the value of the lift coefficient was adjusted so that the model damping ratio should remain lower or equal to that measured experimentally, for the sake of conservatism. As it can be seen from the figure, a very good agreement is obtained. It could be even further improved by taking into account the lift coefficient variation with oscillation amplitude, which was highlighted by Moussou et al (2017).

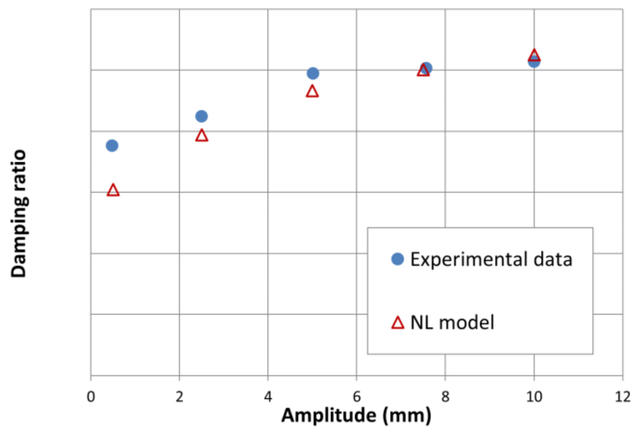


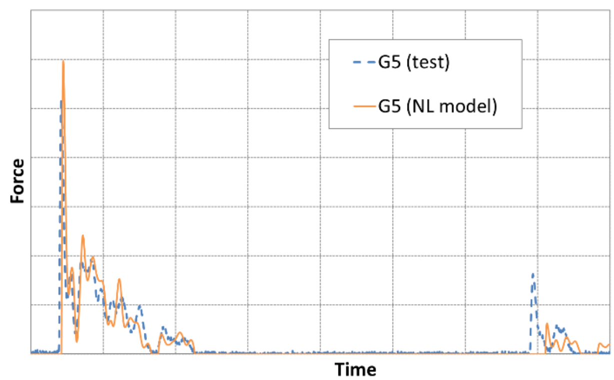
Figure 6: Flow-added damping at 5 m/s

Lateral plucks with impacts at grid levels

A series of lateral plucks with impacts have been simulated on a single fuel assembly model.

As for the forced vibration tests, the model characteristics are representative of the reference 14-feet Framatome FA design in Begin Of Life condition. The initial and boundary conditions are consistent with those of the test, as illustrated on figure 4.b.: the upper and lower extremities of the FA are clamped, initial deflections are imposed at two grid levels (4 and 7) while one or two impact plates are positioned at the level of the 5th and/or 6th grids. The tests are performed in air, at ambient temperature, with amplitudes ranging from 8 to 20 mm.

The main results are illustrated on figure 7 below for lateral plucks of 20 mm amplitude with impacts at the 5th grid level or at both the 5th and 6th grid levels. They are representative of results obtained for other amplitudes.



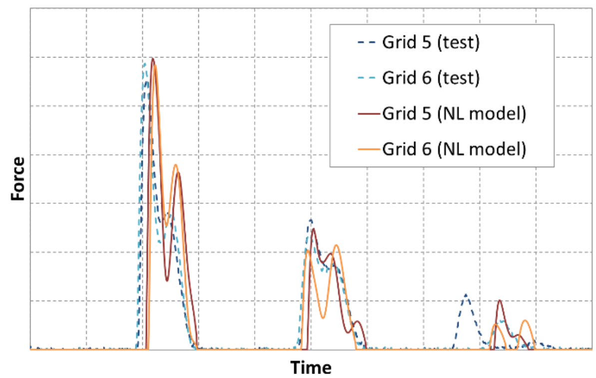


Figure 7: lateral pluck of 20 mm amplitude with impacts at the 5th grid level (left) and at both the 5th and 6th grid levels (right)

As it can be observed, a good agreement is achieved in terms of maximum impact force, impact duration, and successive rebounds. Secondary oscillations of the force time signal, induced by the rod bundle vibration relative to the grid during the impact, are well reproduced by the NL model, thanks to the dedicated rod beam. The deviation in terms of maximum peak force has to be put in perspective considering that no specific calibration was performed for the simulated impact velocity to match the one observed experimentally. This means that deviations with respect to FA natural vibration frequency and structural damping, although minor, do also affect the impact response. Overall, the equivalent impact stiffness which is retrieved by assuming that the relationship between the impact force and the impact velocity as akin to that of a single DoF mass-spring system, is overestimated by 5-15 % typically by the model. This is judged to represent an appropriate level of conservatism for subsequent use of the model for FA safety analyses.

APPLICATION TO FUEL ASSEMBLY ROW DYNAMIC ANALYSIS

Description of application case

With the advanced model having been benchmarked successfully against reference experimental datasets in the previous section, its use for row analysis under dynamic transient can now be considered.

The proposed case corresponds to the simulation of the response of three 12-feet fuel assemblies representative of Framatome technology, subjected to an earthquake transient. The mechanical loading is introduced in the form of motion time-histories applied at the core barrel and core plate nodes, as described in introduction.

Results

The simulations results are presented on figure 8., in terms of maximum impact force for each impact spring of the row. The results obtained for the NL model are compared to those obtained for a similar simulation performed with the reference model.

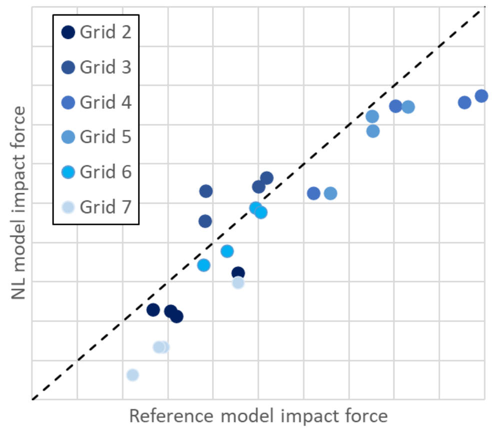


Figure 8: Impact forces at grid levels – comparison between
the reference model and the advanced NL model

As it can be seen on the figure, the results obtained for the NL model are in reasonable agreement with those of the reference model, with the maximum impact force being reduced by about 20 %. Higher forces are observed at the central grids 4 and 5 for both models, which is consistent with the FA response being mostly driven by that of its first natural vibration mode under earthquake excitation.

An additional step of post-treatment showed that, compared to the reference model, the NL model leads to a higher mean impact duration (+20 %) and a lower number of impacts (-15 %). This can be explained as secondary oscillations of the force time-signal, such as the ones highlighted on figure 7., cannot be simulated appropriately by a single beam FA model. Such limitation is likely to lead to artificial rebounds which are judged to be detrimental with regards to both the numerical stability of the simulation and the loadings on internal FA positions, which are the most demanding with respect to the verification of safety requirements.

CONCLUSIONS

An advanced non-linear fuel assembly model has been developed for seismic and LOCA dynamic analyses. Its features have been designed to overcome the limitations of previous models. They result in a reduction of the sources of uncertainties, and an improved accuracy with respect to the prediction of the fuel assembly lateral dynamic behaviour.

The model response has been compared successfully to reference experimental datasets obtained from full-scale fuel assembly tests. Both vibration behaviour (in air and in flowing water) and impact behaviour have been investigated. An exploratory simulation of the response of a row of FAs under earthquake excitation has highlighted a good agreement in general with the prediction of the reference model, as well as some minor differences that will be investigated more thoroughly in future works.

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