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Impact of a hybrid modelling for wall/wall and wall/slab connections on the constructability of reinforced concrete nuclear building

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ABSTRACT

Nuclear installations include many buildings with a reinforced concrete framework of the wall-slab type. The design computation models of these buildings are mostly composed of structural finite elements of plate or shell type. At wall/wall and wall/slab connections, these elements are usually simply extended to the axis of the connection, where perfect transmission of translation and rotation between them is assumed. This practice is particularly prejudicial for nuclear installations with thick walls and slabs.

A hybrid modelling approach where the walls and floors are modelled by shells and the connections between them are represented by 8-node prismatic elements has been proposed by Hervé-Secourgeon (Ph.D. Thesis, 2020) in order to improve the representativeness of the finite element model.

We applied this modelling approach on a complete real building of a nuclear power plant to measure and highlight the effects stated in the work of Hervé-Secourgeon on sample buildings (Ph.D. Thesis, 2020).

The first part of the work consists in creating automatic ANSYS APDL scripts to transform a classic shell model into a complete hybrid model.

The second part of the work consists of carrying out calculations on both usual and hybrid models to assess the optimization brought by this modelling approach:

- on the reinforcement density to install, taking into account the minimum reinforcement and the usual practices of reinforcement in the construction projects of nuclear installations.
- on the floor response spectra (critical for justification of the integrity of equipment)

The main conclusion of the work done around this modelling principles are as follow:

- with the right tools, this kind of modelling is compatible with an industrial use;
- there is a clear reduction of reinforcement for gravitational load cases, however minimum reinforcement and thermal load cases limits the gains we could obtain for an industrial project;
- the impact on the vertical floor response spectra (FRS) is clear: the maximum acceleration is reduced at all tested nodes.

PRESENTATION OF THE HYBRID MODEL

Presentation Of The Modelling Principles

Nuclear installations include many buildings with a reinforced concrete framework of the wall-slab type. In the nuclear industry, the most common practice is to use three dimensional finite elements models to perform the calculations necessary to validate their design. The models of these buildings are essentially composed of structural finite elements of plate or shell type. At wall/wall and wall/slab connections, these elements are usually simply extended to the axis of the connection, where perfect transmission of translation and rotation between them is assumed. If this modelling is perfectly adapted for thinner structural elements, in the case of nuclear building with higher thickness over span ratios the error generated by this modelling is not always negligible. Moreover, several non-physically realistic assumptions are implicitly made when extending the shell elements, such as assuming that tie beam and the slab itself have the same rigidity. Finally, the modelling overestimate span length as well as the total weight of the building as shown on Figure 1.

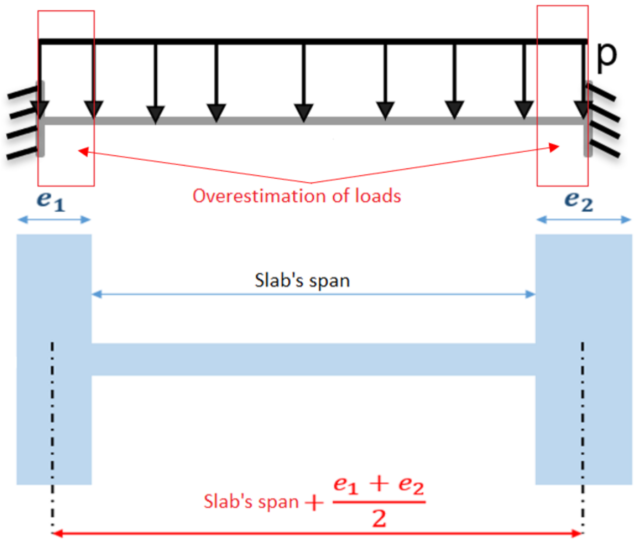

Figure 1. Illustration of error made with standard practice

In the work performed by Hervé-Secourgeon (Ph.D. Thesis, 2020, reference [1]), it is highlighted that a 5% error in the span length of a fixed beam with distributed loads leads to an overestimation of the deflection of 23%, an overestimation of the moment at mid span of 11% and an underestimation of the fundamental frequency of 10%. Such an error, with supporting walls of 500mm targets span length of at least 10m. Such spans are not uncommon in nuclear buildings and reducing these kinds of error can be beneficial for the constructability of new nuclear. Moreover, as pointed out by Hervé-Secourgeon et al in reference [2], high densities of reinforcement are often found in slab/wall connection due in part to poor representation of the D regions.

Thus, a hybrid modelling approach where the walls and floors are modelled by shells and the connections between them are represented by elastic 8-node prismatic elements has been proposed by Hervé-Secourgeon (Ph.D. Thesis, 2020, reference [1]),) in order to improve the representativeness of the finite element model. Then cinematics equations are used to connect these volumes (modelling the D regions) to the shell elements more representative of the B regions of slabs and walls. On Figure 2, a representation of such a connection is shown.

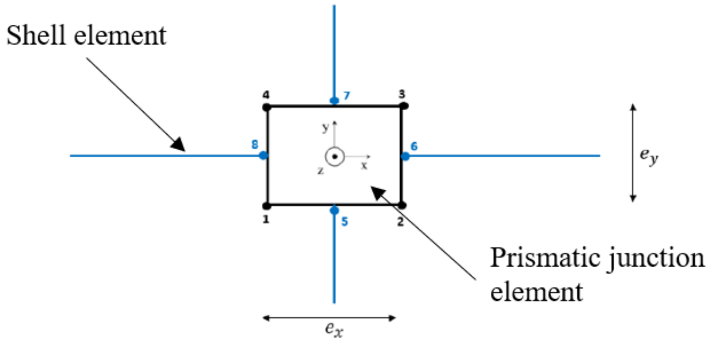

Figure 2. Illustration of hybrid model junction

At the junction presented on Figure 2, the nodes 1,2,3 and 4 are part of a volume and their degree of freedom are three translations: u_{xi} , u_{yi} and u_{zi} , i being the number of the node, and x,y and z the three directions in space. The nodes 5,6,7 and 8 are part of shells, their degree of freedom are three translations and three rotations: θ_{xi}, θ_{yi} and θ_{zi}. Depending of the nature of the liaison slab/wall the cinematics relations can change. For our example, considering fixed walls and slabs, the transmission of movement is translated into cinematic relations (see equation 1 below) between 4 triplets of nodes (1;5;2) , (2;6;3), (3;7;4) and (4;8;1) :

$$\begin{cases} u_{x5} = \frac{u_{x1}+u_{x2}}{2} \\ u_{y5} = \frac{u_{y1}+u_{y2}}{2} \\ u_{z5} = \frac{u_{z1}+u_{z2}}{2} \\ \theta_{z5} = \frac{u_{y2}-u_{y1}}{e_x} \end{cases} ; \begin{cases} u_{x6} = \frac{u_{x2}+u_{x3}}{2} \\ u_{y6} = \frac{u_{y2}+u_{y3}}{2} \\ u_{z6} = \frac{u_{z2}+u_{z3}}{2} \\ \theta_{z6} = \frac{u_{x2}-u_{x3}}{e_y} \end{cases} ; \begin{cases} u_{x7} = \frac{u_{x3}+u_{x4}}{2} \\ u_{y7} = \frac{u_{y3}+u_{y4}}{2} \\ u_{z7} = \frac{u_{z3}+u_{z4}}{2} \\ \theta_{z7} = \frac{u_{y3}-u_{y4}}{e_x} \end{cases} ; \begin{cases} u_{x8} = \frac{u_{x1}+u_{x4}}{2} \\ u_{y8} = \frac{u_{y1}+u_{y4}}{2} \\ u_{z8} = \frac{u_{z1}+u_{z4}}{2} \\ \theta_{z8} = \frac{u_{x1}-u_{x4}}{e_y} \end{cases} \quad (1)$$

Creation Of The Hybrid Model

In order to implement these cinematics relations, as well as the 8 nodes prismatic elements we chose to work from a fully standard model with only shells and beam elements. In order to have some representativeness of nuclear structures, we chose to work on a independent building from an EPR NPP, whose overall dimensions are consistent with most independent buildings. The building chosen has a 27m x46.2m footprint with 50m height distributed on 8 main levels. With no particular need for radioprotection, structural thicknesses are not as high as in other buildings (as such as fuel building or reactor building). The thickness range of slabs is 0.5m to 1m and thickness range for walls is 0.4m to 1.2m. The starting model has been developed in ANSYS for global calculation and integrate all necessary gravitational loads (equipment, dead loads, and live loads) as well as an ISS by means of grids of springs emulating the soil stiffness.

To obtain a hybrid model, a chain of scripts is written in APDL language in order to have an automatic process. The chain of scripts works as follows and is illustrated on Figure 3:

- Stage 1. Identification of walls and slabs, works by regroupings elements within the same plane;
- Stage 2. Identification of nodes at wall/wall and wall/slab junction, works by identifying common nodes within two planes;
- Stage 3. 8 nodes prismatic elements creation at the junction, using shells thickness as a way to provide the volume dimensions;
- Stage 4. Shift of any mass element now in the volume to the edge of the volume;
- Stage 5. Shift of edge shell element nodes to the volume border and cinematic relation creation and deletion of shell elements at the junction.

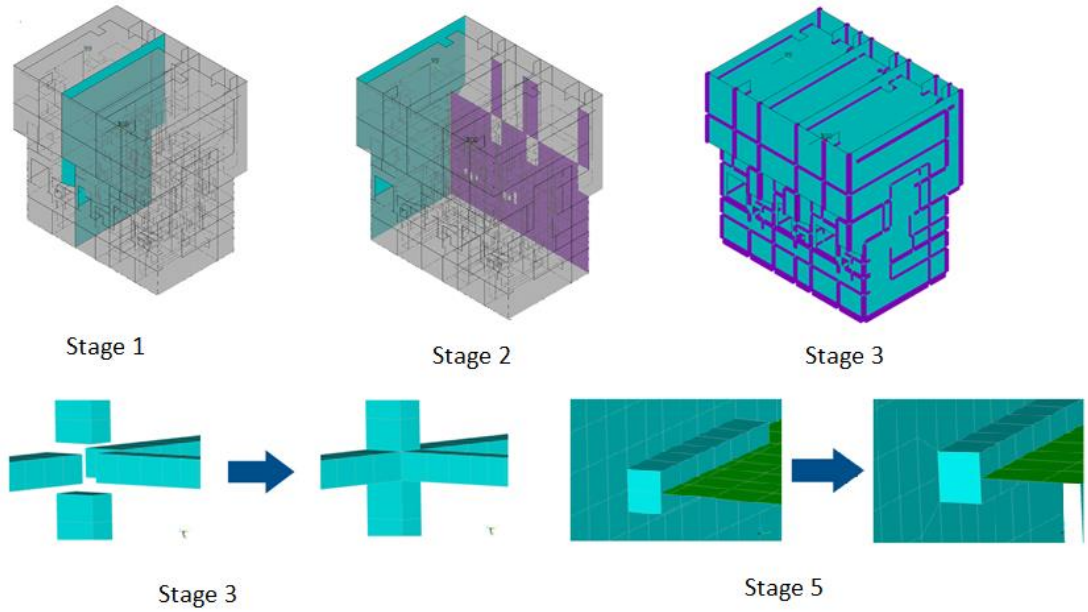

Figure 3: Illustration of the modification of a shell only model

The automatic generation is checked at least visually at each stage, but most importantly it is checked by comparing the initial model deformation (static and modal shapes) against the hybrid model. Small shifts of frequencies are expected but modal shapes and static deformation should be similar, examples provided in Figure 4 to Figure 7 shows that it is the case.

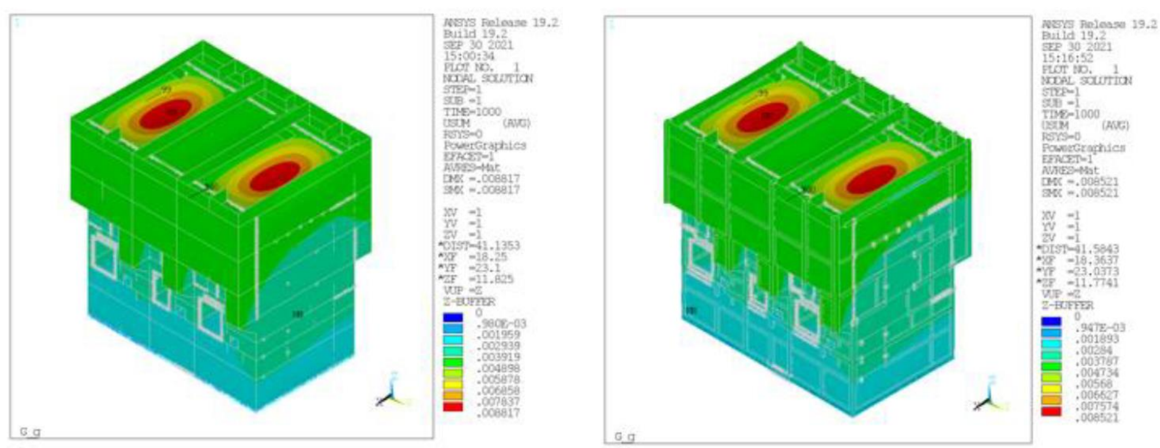

Figure 4: Comparison of static displacements between the reference model (left) and the hybrid model (right)

One other aspect of this modelling was to reduce the total weight of the building. By comparing the building used for dynamic analysis (Permanent loads G + one fifth of live loads 0.2Q) we obtain a reduction of the total load from 68 767t to 64 362t i.e., a reduction of 6,40%. This reduction of weight is not the sole reason of the frequencies shifts, showing that the global rigidity of the models is changed by the modelling. Nevertheless, the frequency shift of the main eigenfrequencies remain lower than 10%. For local modes the frequency shift can be higher.

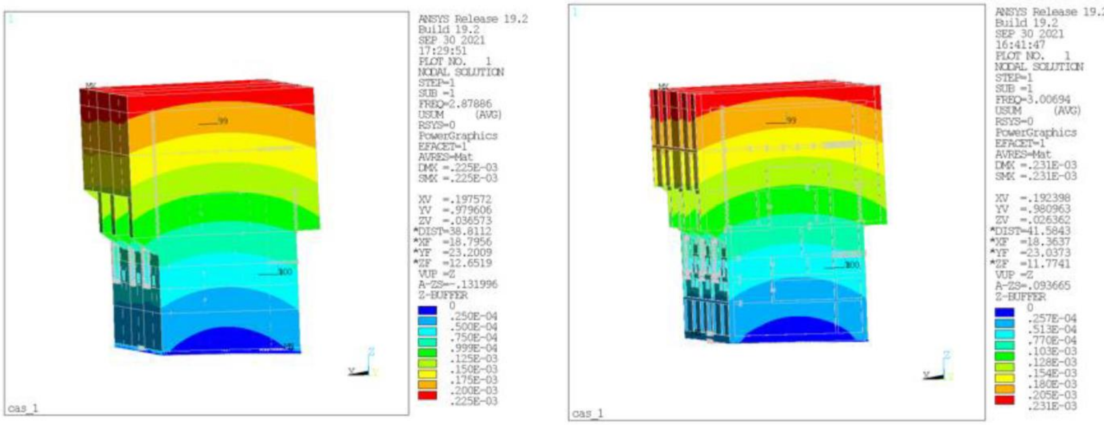

Figure 5: Comparison of first mode between the reference model (left, 2.9Hz)) and the hybrid model (right, 3.0Hz)

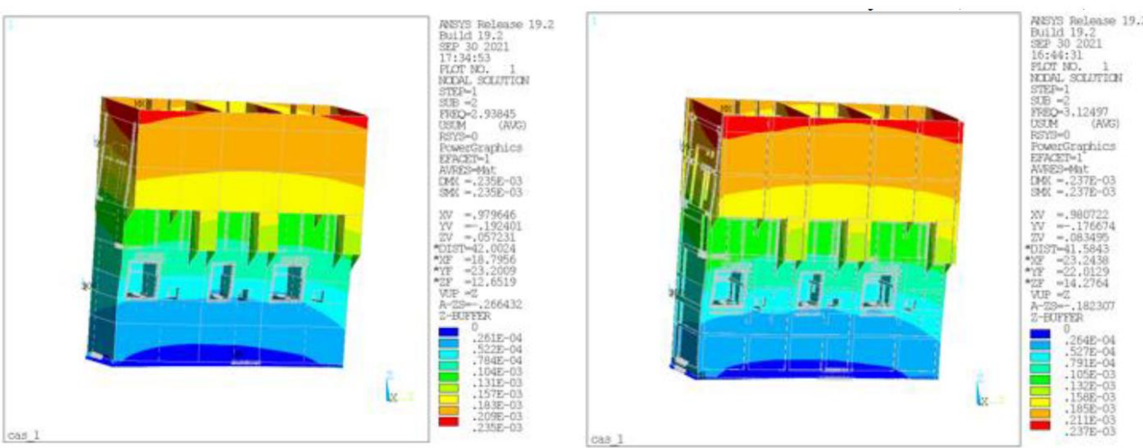

Figure 6: Comparison of second mode between the reference model (left, 2.9Hz)) and the hybrid model (right, 3.1Hz)

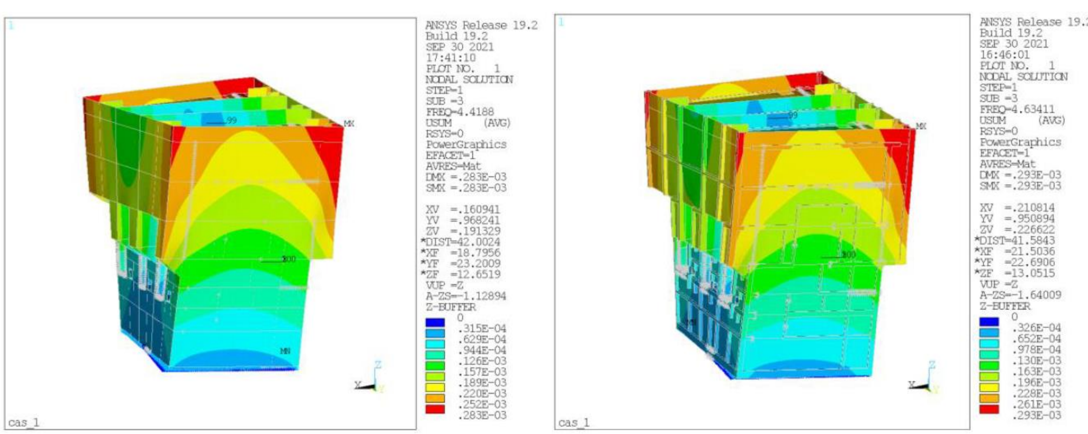

Figure 7: Comparison of third mode between the reference model (left, 4.4Hz)) and the hybrid model (right, 4.6Hz)

IMPACT ON REINFORCEMENT DENSITIES

Elementary Load Cases And Combinations

The aim of the test being to evaluate the potential gains in reinforcement for new nuclear projects and not a complete design, the focus is on a few elementary load cases always present in the design of buildings:

- Permanent actions: building self-weight, earth/water pressures and permanent overload on slabs and walls. All these actions are identified by the letter G_k. To these actions the permanent temperature $G_{k,th}$ is added;
- Variable actions: temperatures (Winter, Summer) identified by $Q_{k,th}$, live loads identified by $Q_{k,l}$;
- Accidental action: design earthquake (EUR -European Utility Requirements - medium soil with a 0.25g zero period acceleration (ZPA) shown on Figure 8) identified by A_{DE}.

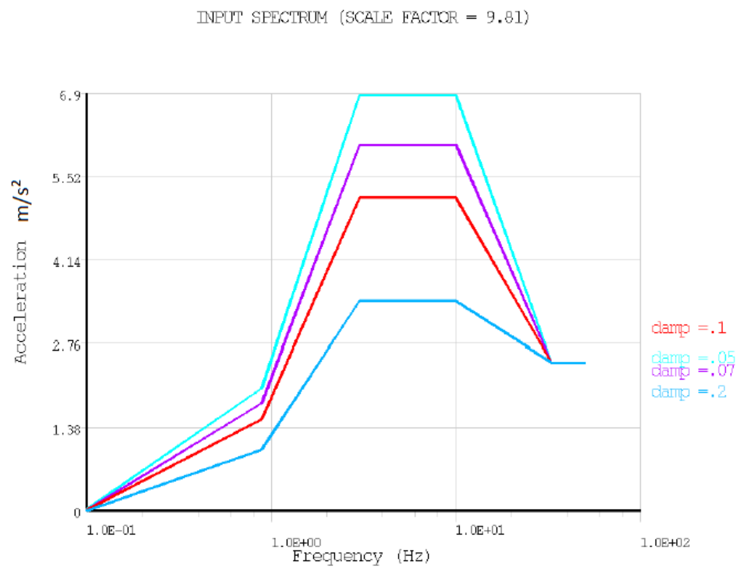

Figure 8: Horizontal Seismic Acceleration Spectra

These load cases are defined according to RCC-CW 2018 and their combinations are separated into four limit states:

- Serviceability limit state, quasi permanent (SLS,qp) :
  - $1.00\ G_k + 0.60\ G_{k,th} + 0.30\ Q_{k,L}$
- Serviceability limit state, caracteristic (SLS,c) :
  - $1.00\ G_k + 0.50\ G_{k,th} + 1.00\ Q_{k,L} + 0.30\ Q_{k,th}$
  - $1.00\ G_k + 0.50\ G_{k,th} + 0.70\ Q_{k,L} + 0.50\ Q_{k,th}$
  - $1.00\ G_k + 0.50\ G_{k,th} + 1.00\ Q_{k,L} + 0.30\ Q_{k,th} + 0.20\ A_{DE}$
- Ultimate limit state, fundamental (ULS,f) :
  - $1.35\ G_k + 0.50\ G_{k,th} + 1.50\ Q_{k,L} + 0.45\ Q_{k,th}$
  - $1.35\ G_k + 0.50\ G_{k,th} + 1.05\ Q_{k,L} + 0.75\ Q_{k,th}$
- Ultimate limit state, accidental (ULS,a) :
  - $1.00\ G_k + 0.35\ G_{k,th} + 0.30\ Q_{k,L} + 0.18\ Q_{k,th} + 1.00\ A_{DE}$

Each combination results are combined according to RCC-CW 2018 rules and reinforcement sections are computed using the Capra-Maury algorithm in the shell elements of both models.

Reinforcement Calculation Results

The first step is to compare the raw calculations, without introducing any minimum reinforcement ratio. For each shell element, the maximum reinforcement section in any combination is extracted for each reinforcement direction (4 longitudinal and 1 transversal). The 5 sections are cumulated to give, in each shell element, a reinforcement density. When comparing the two models, for both slabs and walls (Figure 9), reinforcement densities computed using the hybrid model are statistically lower than those computed with the reference model.

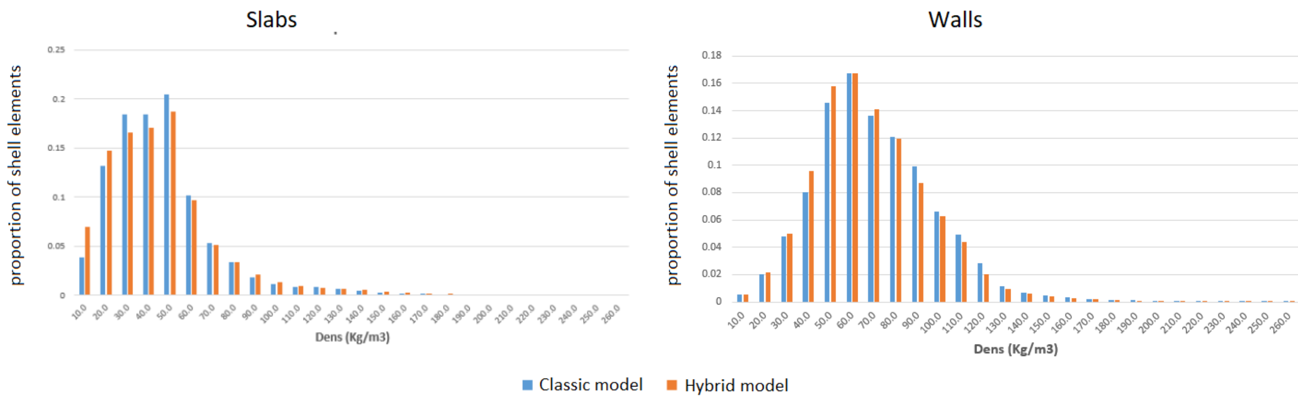

Figure 9: Raw reinforcement results comparison for slabs and walls

If the raw results comparison shows a reduction in reinforcement densities, in a new nuclear project a high minimum reinforcement density value is applied for each structural element. When accounting for it, a difference can still be seen but it is less apparent, as show in Figure 10.

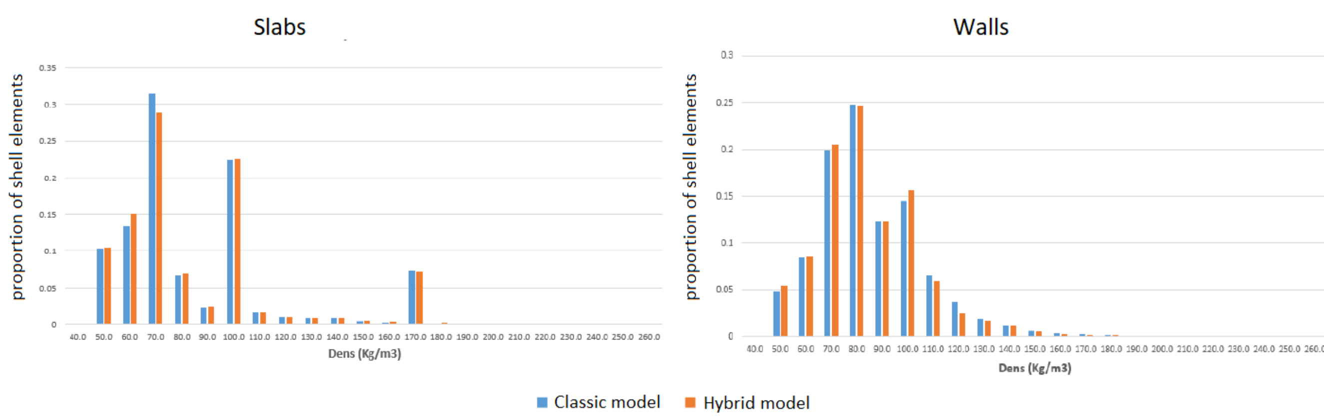

Figure 10: Reinforcement results comparison for slabs and walls accounting for minimum reinforcement

Thus, even accounting for minimum reinforcement, reinforcement densities can be optimised by a hybrid models, meaning that constructability can be improved. Moreover, by comparing the areas where reinforcement are significantly lower with the hybrid model it appears that the reinforcement gain exists when the enveloping combination is part of the ultimate state family (as illustrated on Figure 11). By looking at the combination factors, that means that measurable reinforcement gain is expected when the mechanical loads are higher in comparison than the thermal loads.

This is in agreement with the expected results, as the hybrid model enables a better representativity regarding flexure loads only. Membrane loads effect remains unchanged.

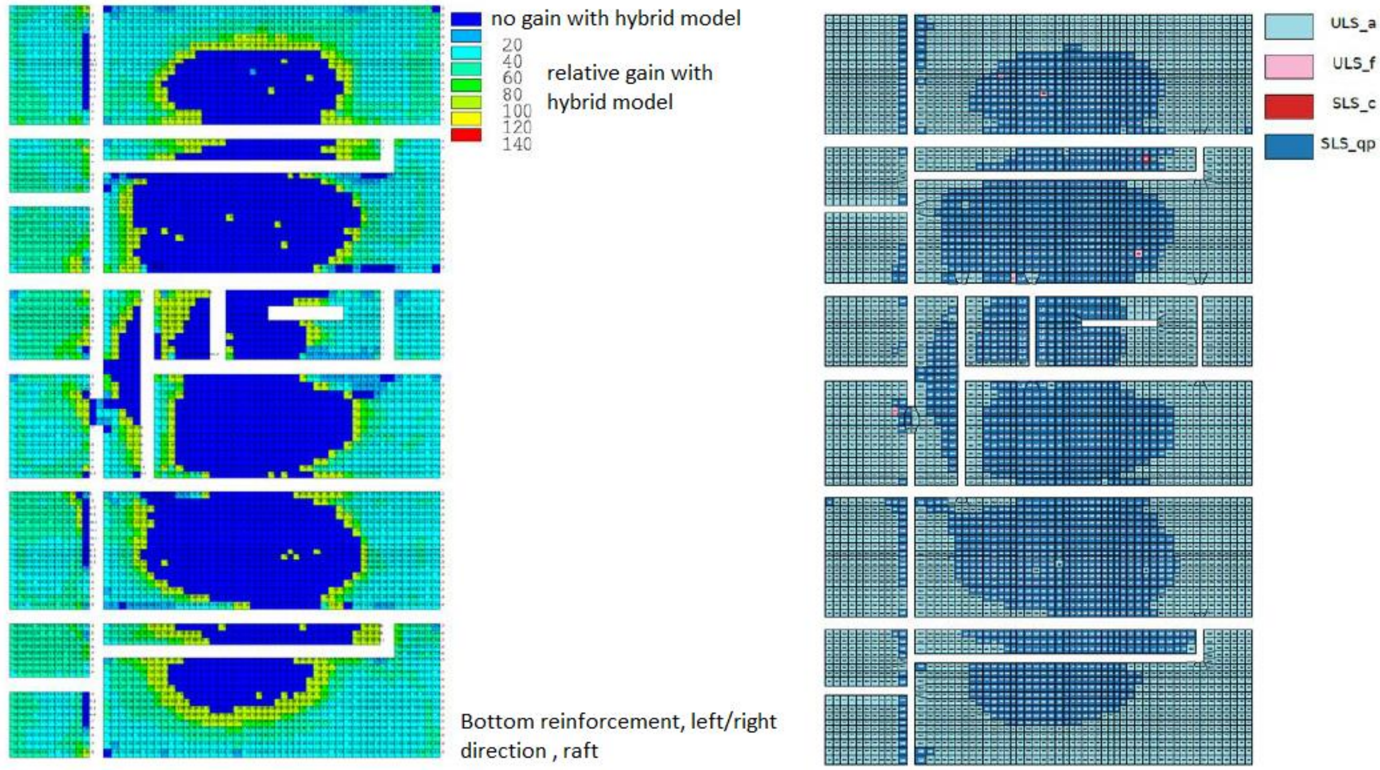

Figure 11: Reinforcement gains and enveloping combination

IMPACT ON FLOOR RESPONSE SPECTRA

Another expected influence of the hybrid modelling is a reduction of acceleration in the transferred floor response spectra (FRS). A reduction of these accelerations is also a tool to improve constructability. Indeed, the FRS are used as de-coupling tools to design equipment and high acceleration are coming back to the civil structures as high anchoring forces and over dimensioned anchorages.

As for the design earthquake, the EUR medium soil spectra (0.25g) are used for the calculation of FRS. Three accelerograms are generated from the input spectra at 5% damping. Three accelerograms are used as input motion in each direction and are permutated to get 3 sets of input movement. The accelerogram applied in the vertical direction is factored by 2/3. For each of these three input motions, a time-history calculation based on the modal decomposition method is performed. For each of these three permutations, the transferred response spectra are calculated at selected nodes representative of the global movement of the building, as shown on Figure 12.

Then for each node, the transferred response spectra are obtained by taking the average value of the three different calculations carried out with permutation of the three acceleration time histories. Then for each direction (X,Y for the two horizontal direction and Z for the vertical direction), the FRS for one level is the envelop of each nodes average FRS.

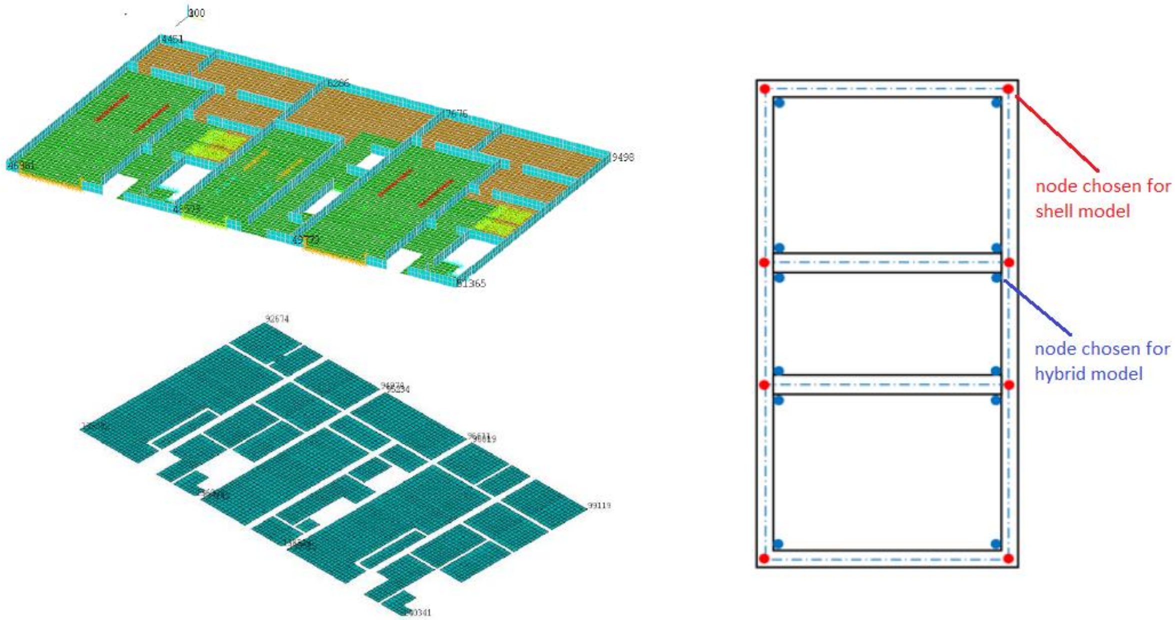

Figure 12: Chosen extraction node at level +0.00m

Each level is post-processed, and the FRS are compared. The first thing to look at is the shape of FRS. As expected, the shapes are very similar, as shown for the floor 6 (vertical direction) in the Figure 13:

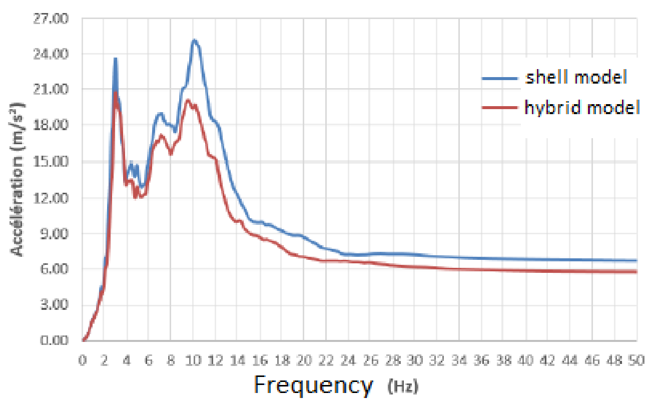

Figure 13: Floor 6 vertical responses spectra for both models

For each direction, and for each floor several values are compared between the two models, each of these values allows to paint the same picture as the one found in the work of Hervé-Secourgeon on sample buildings (Ph.D. Thesis, 2020), all of the following results are illustrated on Figure 14 :

- The peak accelerations in the horizontal directions are in a range of ±15% depending of the direction and the floor
- The peak acceleration in the vertical direction are always lower, up to 20%, with the hybrid model
- The ZPA in the horizontal directions are in a range of ±7% depending of the direction and the floor
- The ZPA in the vertical directions are always lower, up to 15%, with the hybrid model

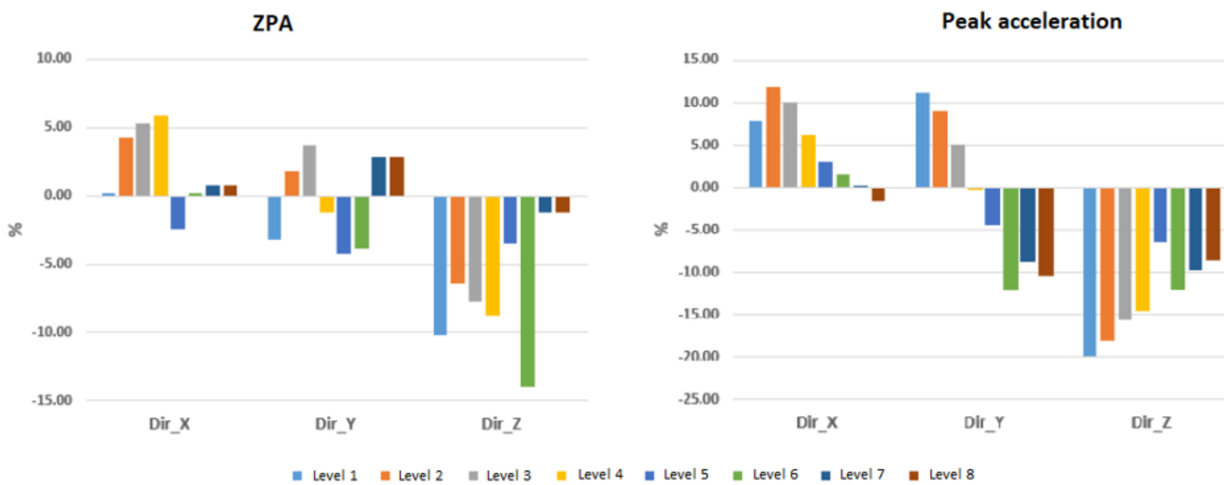

Figure 14: Relative difference between the shell model FRS and the hybrid model (negative when shell accelerations are higher)

PERSPECTIVES

The first conclusion of this work is that the implementation of this method is feasible on an industrial level. With our automatic script the amount of work necessary to transform a shell model to a hybrid model is around 2 to 3 days including all the necessary checks. A full automation is achievable, even with a real nuclear building complex design, and is one of the main perspectives to explore.

On the reinforcement calculation, the expected reinforcement gains are limited by minimum reinforcement and thermal actions. With this conclusion, to path of exploration can be defined : the first being the optimization of the way thermal actions are computed in the mathematical model and the second being charting the key dimensions allowing to predict which building will benefit more of this kind of modelling.

Finally, on the FRS calculation, the fact that the vertical accelerations are reduced is a good result in itself as the anchoring forces the most penalizing for the concrete are the tension forces. As for the reinforcement calculation, further work should focus on the characterization of the type of building which will benefit the most of this kind of modelling.

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