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EFFECT OF SHELL ELEMENT MESH SIZE ON FINITE ELEMENT RESULTS

Tasho Naumov[1], John Hadfield[2], Ming Tan[3]

[1] Principal Structural Engineer, Mott MacDonald, BG (tasho.naumov@mottmac.com)
[2] Principal Structural Analyst, Mott Macdonald, UK (john.hadfield@mottmac.com)
[3] Technical Principal, Mott Macdonald, UK (ming.tan@mottmac.com)

ABSTRACT

This paper presents a study into the sensitivity of analytical results due to mesh size, considering typical for nuclear structures wall and slab models and loading regimes The results are presented in graphical and tabular format, followed by their interpretation in the discussion section and a concise conclusion section.

The study presented herein reiterates the need for the structural analysis and design practitioners to have in-depth knowledge of how the finite element results are output and what specific measures need to be taken into account in terms of mesh-size when building the model, so that the results used for the design of structural members do not adversely impact the design and ultimately, nuclear safety.

INTRODUCTION

Relevant good practice for finite element analysis, such as outlined in ASCE/SEI 4-16 (2017), sets a requirement for performing a mesh density study as part of the Verification and Validation procedures for finite element analysis, however, no specific guidance is usually provided, and analysts and structural engineers develop their own standardised approaches to dealing with that requirement. Some of the critical considerations that need to be taken into account when constructing the structural analysis FE model and when generating output data for use in global structural design are outlined in this paper.

When performing Finite Element (FE) analysis as part of the design for new nuclear structures, it is a well-known problem that in many cases the modelled shell element mesh size has an influence on the accuracy of the analytical results when directly extracting the results from the FE analysis software. This is often due to the averaging of the element's nodal force and moment results in order to give single 'centroidal' result item value per element (as opposed to a value at each node), which is convenient for the purposes of design. A fine mesh therefore typically produces more accurate results than a coarse mesh when averaging.

Concrete slab and wall models with their respective loading regimes, appropriate to nuclear structures, are considered for this study. Various mesh sizes are created for each slab and wall model and analysed using the general purpose FE software ANSYS (Mechanical APDL, 2021). The results (bending moments, in-plane forces, out-plane shear forces) are compared between the various mesh sizes, considering specific locations representative of the critical sections used for the design of Reinforced Concrete (RC) structural members as defined in different nuclear design codes, eg. ACI 349M-13 (2015).

The study described in this paper was developed using the work undertaken for the Generic Design Assessment (GDA) in the UK for the UK HPR1000 (GDA, 2020).

UK HPR1000

The UK HPR1000 is a Pressurised Water Reactor using the Chinese Hualong technology with an electric output of approximately 1180MW. The UK HPR1000 is developed from a series of reactors that have been constructed and operated in China since the late 1980's, including the M310 design used at Daya Bay and Ling'ao Units 1 & 2, the CPR1000, the CPR1000+, and the more recent ACPR1000. The first two units of CGN's HPR1000, Fangchenggang NPP Units 3 & 4, are currently under construction in China. Fangchenggang NPP Unit 3 is the reference plant for the UK HPR1000.

With the intention of being deployed at the Bradwell 'B' site in the UK, the UK HPR1000 was put forward for GDA in January 2017, to be assessed jointly by the regulators – the Office for Nuclear Regulation (ONR) and the Environment Agency. The regulators provided independent scrutiny to ensure that the reactor design is applicable to UK regulatory standards of safety, security and environmental protection. The GDA for the UK HPR1000 was successfully completed in February 2022, with the issuing of a Design Acceptance Confirmation (DAC) from the ONR and a Statement of Design Acceptability (SoDA) from the Environment Agency (ONR, 2022).

METHOD

The method of developing the study presented in this paper is carefully selected to be in accordance with relevant good practice for global structural analysis and design in the nuclear industry. The method utilises FE models constructed from shell elements within ANSYS (Mechanical APDL, 2021). Such practice often requires the use of automated design procedures using single centroidal result item values for each modelled shell element for each relevant load. This study is therefore based on simple analytical models constructed from shell elements with centroidal analytical output for each element.

A total of 3 FE models (2 concrete slab and 1 concrete wall), each with varying mesh size, are developed to demonstrate the influence of the size and arrangement of the shell mesh on the analysis output. These 3 models are summarised as follows:

- Larger RC Slab - representative of medium to long span slab panels (Figure 1)
    - Dimensions of 4.9m by 10.4m.
    - Thickness of 0.5m.
    - Fixed boundary conditions on all 4 edges (ie. at supporting walls).
    - Uniformly distributed loading out-plane on all elements.
- Narrower Long RC Slab - representative of short span slab panels
    - Dimensions of 2.7m by 12.3m (ie. one-way spanning such as for corridors).
    - Thickness of 0.5m.
    - Fixed boundary conditions on all 4 edges.
    - Uniformly distributed loading out-plane on all elements.
- RC Wall – representative of typical wall construction (Figure 2)
    - Dimensions of 4.7m by 10.4m high.
    - Thickness of 0.8m.
    - Fixed boundary condition on bottom edge (other edges free).
    - Horizontal forces applied in-plane on top edge nodes.

The 2 slab models are used to illustrate results from typical out-plane floor loading (ie. vertical loading). The wall model is used to illustrate results from typical in-plane shear loading (ie. also from horizontal loading). Thus a wide range of possible design scenarios are covered.

As seen in Figure 1 and Figure 2, a total of 4 different mesh sizes are used for each model, as follows:

- reference – 0.2m mesh size (high resolution).
- 0.5m mesh size.
- 0.75m mesh size.
- 1.5m mesh size.

These element sizes are chosen so that the finest element size, 0.20m, serves as reference for the comparison of the results, with the other mesh sizes being as typically used for static and dynamic structural analyses in the nuclear industry for concrete building models.

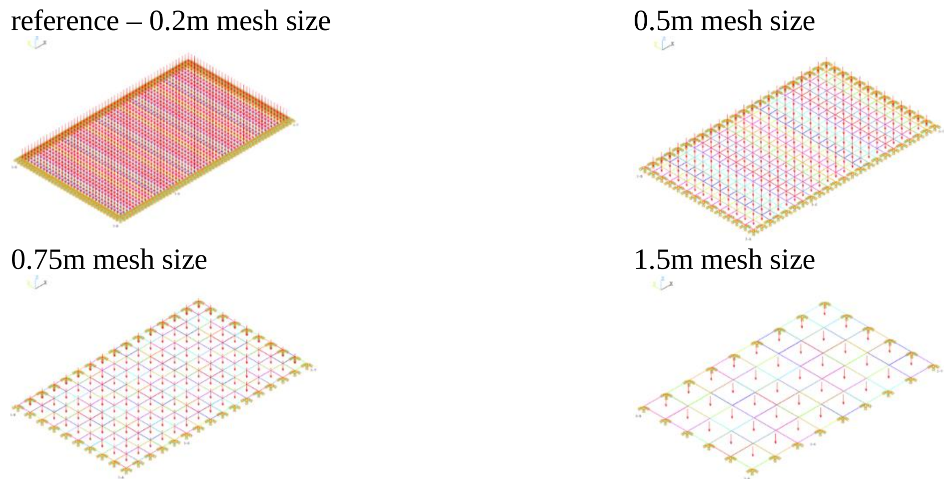

Figure 1. Larger RC Slab - FE Modelling

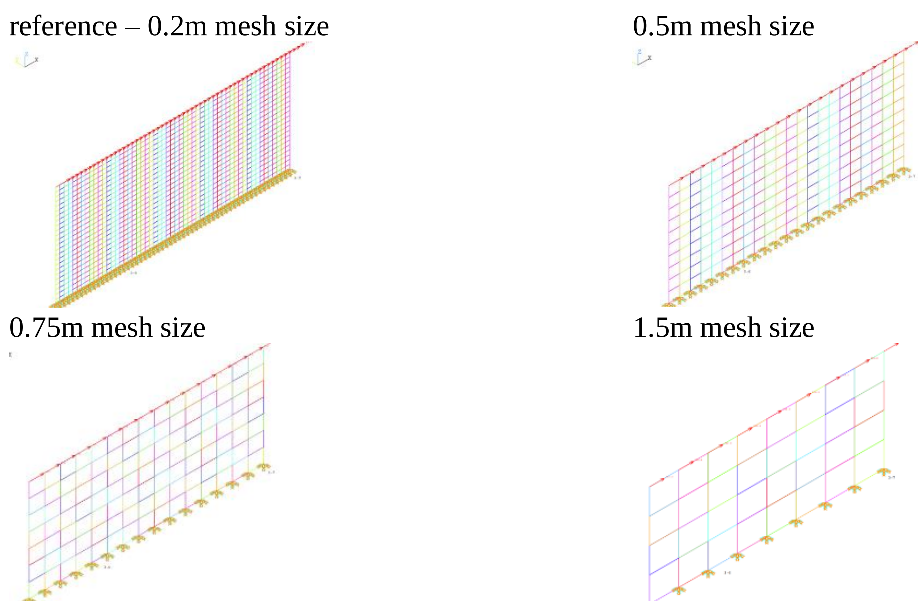

Figure 2. RC Wall - FE Modelling

RESULTS

The results from all 3 models are extracted at the critical sections appropriate to the design of slabs and walls:

- For out-plane slab bending - critical sections at the centre for sagging bending moments, and at edges for hogging bending moments.
- For out-plane slab shear - critical sections at a distance from edge equal to the effective depth of the cross section.
- For in-plane wall axial forces – critical sections at a zone smaller than the minimum length of the wall boundary element in accordance with Section 21.9.6.4(a) of ACI 349M-13 (2015).
- For in-plane wall shear – use maximum value from any of the shell elements.

The shell element force and moment results are extracted from ANSYS to give the centroidal result item values (using the ANSYS etable command, or calculating from the nodal reactions, ie. non-averaged, where shown in italics in the last columns for each tabular result representation shown below). Plots of the results for the various mesh sizes are shown in the figures below for the models, and are also tabulated. All values are kN and m based.

On Figure 3 below, the bending moment (My) is presented for the Larger RC Slab.

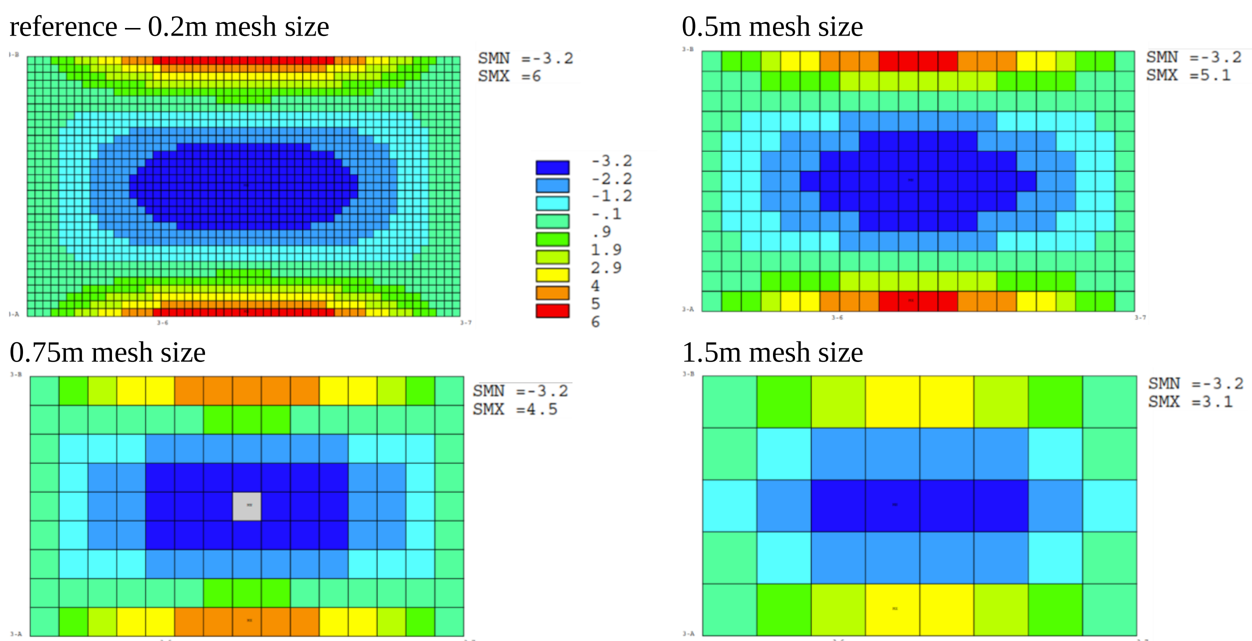

Figure 3. Larger RC Slab – Bending Moment

Corresponding bending moment values for the Larger RC Slab along the central cut-line are shown in Figure 4 and tabulated in Table 1. The values in Table 1 are taken at a distance from the edge of the supporting walls equal to the supporting wall thicknesses.

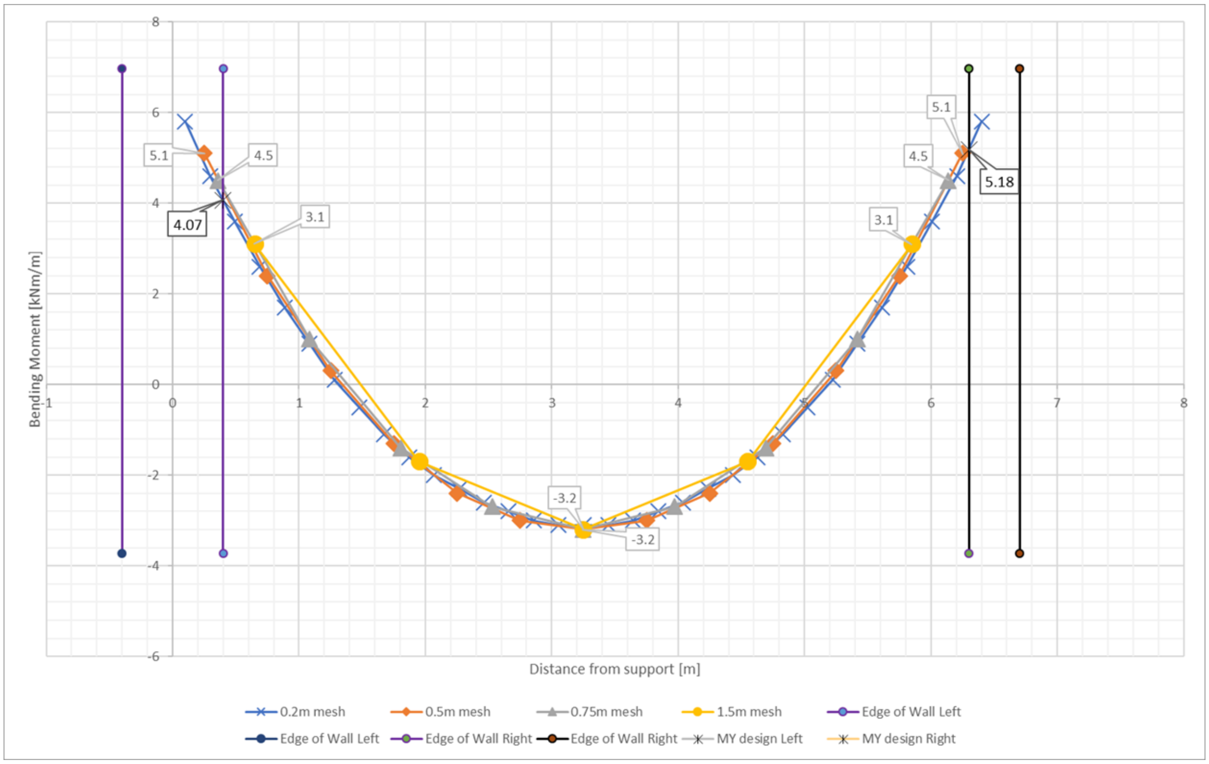

Figure 4. Larger RC Slab – Bending Moment; Values Along Central Cut-Line

Table 1: Larger RC Slab - Bending Moment; Values Along Central Cut-Line

	0.2m	0.5m	variance to 0.2m	0.75m	variance to 0.2m	1.5m	variance to 0.2m	*1.5m*	*variance to 0.2m*
at left support (use supporting wall thickness of 0.8m)	4.1	5.1	25%	4.5	11%	3.1	-24%	*6.6*	*62%*
at centre	-3.1	-3.2	3%	-3.2	3%	-3.2	3%	*-3.3*	*6%*
at right support (use supporting wall thickness of 0.4m)	5.2	5.1	-2%	4.5	-13%	3.1	-40%	*6.6*	*27%*

The out-plane shear force (Qy) values for the Larger RC Slab along the central cut-line are shown in Figure 5 and tabulated in Table 2. The values in Table 2 are taken at a distance from the edge of the supporting walls equal to the effective depth (d) of the slab.

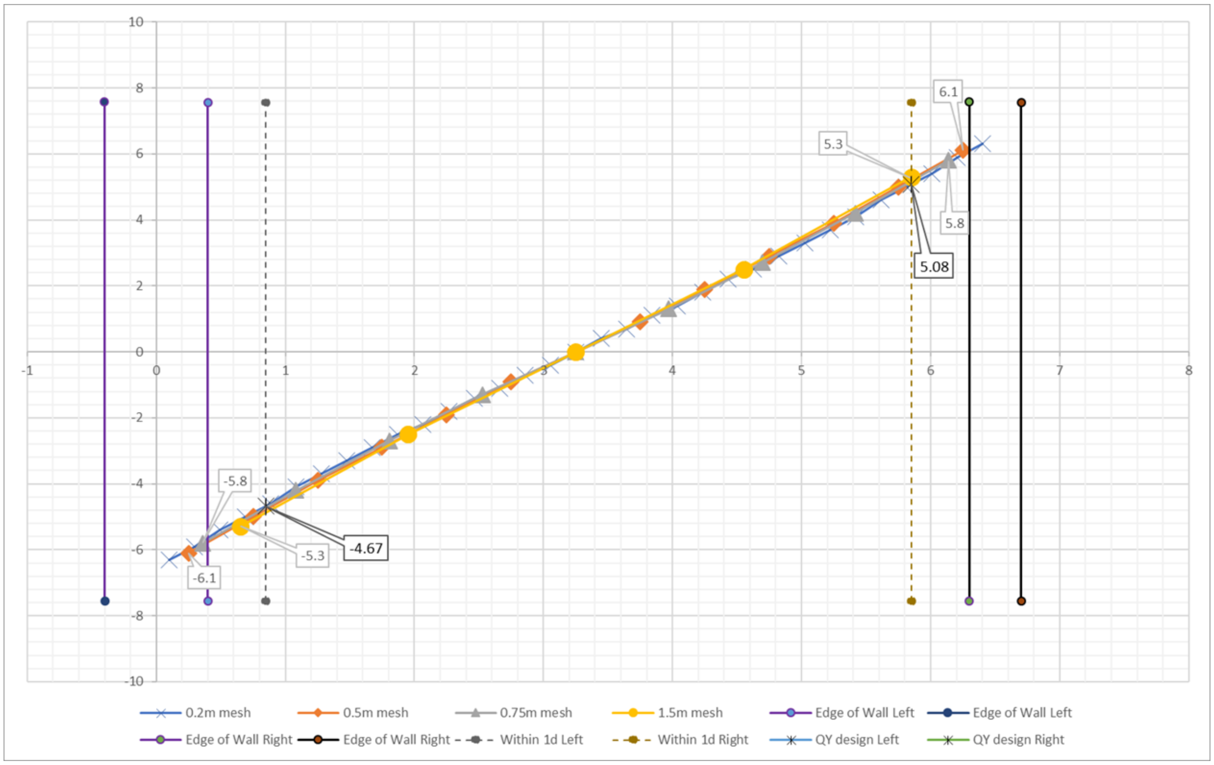

Figure 5. Larger RC Slab - Out-Plane Shear Force; Values Along Central Cut-Line

Table 2: Larger RC Slab - Out-Plane Shear Force; Values Along Central Cut-Line

	0.2m	0.5m	variance to 0.2m	0.75m	variance to 0.2m	1.5m	variance to 0.2m	*1.5m*	*variance to 0.2m*
at 1xd from left support	-4.7	-6.1	31%	-5.8	24%	-5.3	13%	*-6.7*	*43%*
at 1xd from right support	5.1	6.1	20%	5.8	14%	5.3	4%	*6.7*	*32%*

The bending moment (Mx) values for the Narrower Long RC Slab along the central cut-line are tabulated in Table 3. The values in Table 3 are taken at a distance from the edge of the supporting walls equal to the supporting wall thicknesses.

Table 3: Narrower Long RC Slab - Bending Moment; Values Along Central Cut-Line

	0.2m	0.5m	variance to 0.2m	0.75m	variance to 0.2m	1.5m	variance to 0.2m	*1.5m*	*variance to 0.2m*
at left support (use supporting wall thickness of 1.5m)	0.1	1.5	2338%	1.1	1688%	0.5	713%	*2*	*3150%*
at centre	-1.1	-1.1	0%	-1.1	0%	-1.0	-9%	*-1*	*-9%*
at right support (use supporting wall thickness of 0.5m)	1.4	1.5	5%	1.1	-23%	0.5	-65%	*2*	*40%*

The out-plane shear force (Qx) values for the Narrower Long RC Slab along the central cut-line are tabulated in Table 4. The values in Table 4 are taken at a distance from the edge of the supporting walls equal to the effective depth (d) of the slab.

Table 4: Narrower Long RC Slab - Out-Plane Shear Force; Values Along Central Cut-Line

	0.2m	0.5m	variance to 0.2m	0.75 m	variance to 0.2m	1.5m	variance to 0.2m	*1.5m*	*variance to 0.2m*
at 1xd from left support	-1.3	-3.2	139%	-3	124%	-2.5	87%	*-3.7*	*176%*
at 1xd from right support	2.3	3.2	41%	3	32%	2.5	10%	*3.7*	*63%*

On Figure 6 below, the in-plane axial force (Nx) is presented for the RC Wall.

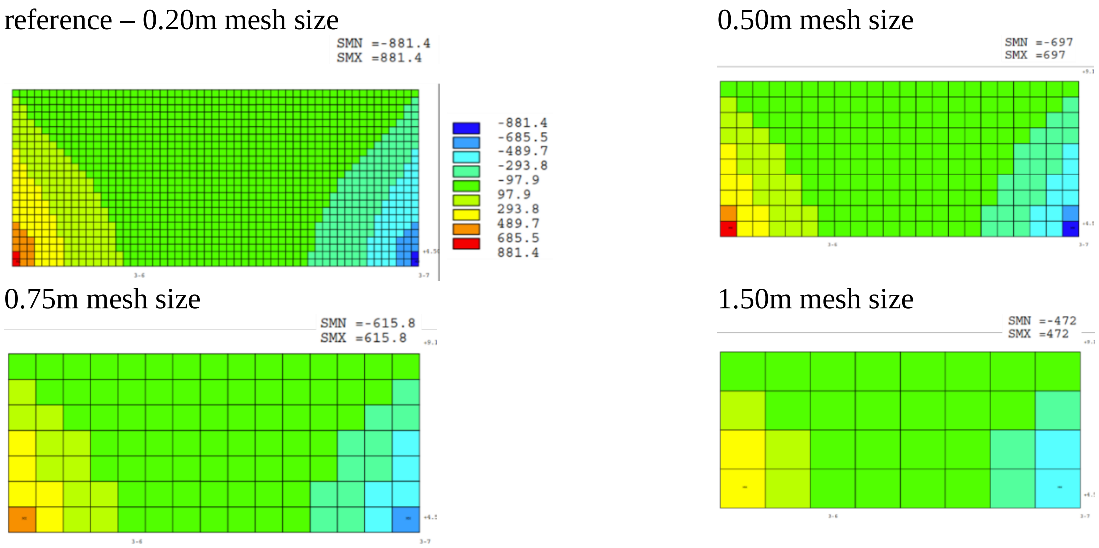

Figure 6. RC Wall - In-Plane Axial Force

Corresponding in-plane axial force values for the RC Wall are tabulated in Table 5.

Table 5: RC Wall - In-Plane Axial Force

	0.2m	0.5m	variance to 0.2m	0.75m	variance to 0.2m	1.5m	variance to 0.2m	*1.5m*	*variance to 0.2m*
averaged for zone 1.356m wide at wall end	516	487	-6%	481	-7%	472	-9%	*653*	*27%*

On Figure 7 below, the in-plane shear force (Nxy) is presented for the RC Wall.

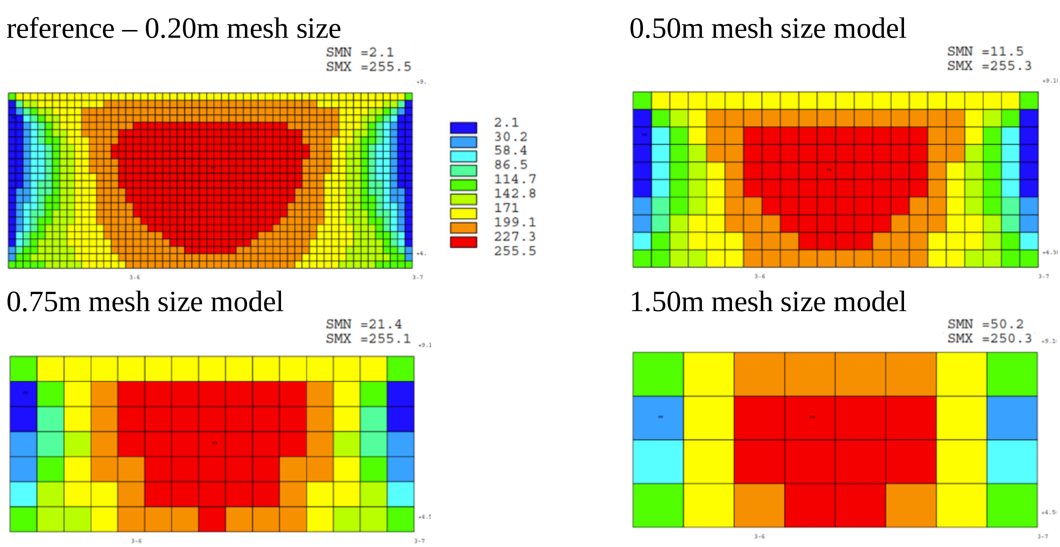

Figure 7. RC Wall - In-Plane Shear Force

Corresponding in-plane shear force values for the RC Wall are tabulated in Table 6.

Table 6: RC Wall - In-Plane Shear Force

	0.2m	0.5m	variance to 0.2m	0.75m	variance to 0.2m	1.5m	variance to 0.2m
maximum value from any of the shell elements	256	255	0%	255	0%	250	-2%

DISCUSSION

An interpretation of the results for bending moments, in-plane forces, and out-plane shear forces from the various FE analyses is developed. The interpretation is driven by practical considerations in terms of global structural design for typical RC structural elements commonly used in the nuclear industry. The items discussed below represent typical phenomena driving the design of RC structural elements – ie. bending moments and out-plane shear forces for horizontal structural elements (slabs) and in-plane forces for vertical structural elements (walls).

Based on the results from the analyses, for sagging bending moments at the centre of the span there is no significant variation in the results for all mesh sizes and for both RC slab configurations and support conditions. This is valid for both the averaged centroidal values, and the non-averaged nodal values.

For hogging bending moments at critical sections at the supports, the results can vary significantly depending on the mesh size and other considerations, as summarised below:

- For the 0.50m mesh size and averaged centroidal values, the results for both the larger RC slab and the narrower long RC slab panels can be considered adequate, and also in the case of thinner (~ 400mm thick) supporting walls - since the under conservatism of the results compared to the 0.2m mesh size is less than 10%.
- For the 0.75m mesh size and averaged centroidal values, at thinner (~400mm thick) supporting walls, and the larger RC slabs, the under-conservatism can exceed 10%. For the narrower long RC slabs the under-conservatism can exceed 20%. For walls of medium thickness (~ 800mm thick) the results are considered adequate.
- For the 1.50m mesh size and averaged centroidal values, the under-conservatism in case of thinner supporting walls can exceed 60% for the narrower long RC slab configuration, and 40% for the larger RC slab panels. Only for thicker walls (> ~1500mm thick), are the results considered adequate. It is noted that using the non-averaged nodal values can remove the under-conservatism - however, this can lead to significant overdesign, although it does provide a viable alternative solution to justify the use of a larger mesh size.

For out-plane shear forces the averaged centroidal values for all configurations and mesh sizes is considered adequate, as no under-conservatism is expected based on the comparison of results provided above. This is mainly due to the offset of the critical section towards the interior of the RC structural elements.

Based on the results from the wall model analyses, for axial in-plane forces using the averaged centroidal values, all mesh sizes are considered adequate. However, careful consideration of the mesh size with regards to any geometrical design requirements, as discussed above in the results section, needs to be addressed. It is noted that in the case of thinner walls and larger mesh sizes (>~1.50m), the averaged centroidal values may tend towards being under-conservative. However, using the non-averaged nodal values can provide a viable alternative solution.

In the case of in-plane shear forces, the averaged centroidal values for all mesh sizes can be considered adequate.

CONCLUSION

Mesh size and arrangement in the finite element analysis is key for the adequacy of the analysis output for conventional structural design of nuclear related facilities. Some of the critical considerations that can significantly impact output results are structural elements' thicknesses, geometrical arrangement of the mesh, and type of element force output. Provided these considerations are carefully implemented in the building of the FE model and when extracting output results, using larger mesh size can be both practical and feasible.

The geometrical constraints mentioned can relate to specific design requirements such as position of critical sections where adequate output is generated, as well as zones within structural elements where the results from the FE analysis can be placed together. Such zones in this study were demonstrated to be the wall boundary elements.

The adequate processes for generation of output data can relate to the method of averaging the elemental results, ie. using averaged centroidal values, and the non-averaged nodal values.

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