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DESIGN OF REINFORCED CONCRETE STRUCTURES USING SECTION CUTS IN ANSYS

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ABSTRACT

Reinforced Concrete (RC) structures are a critical component of Nuclear Power Plants (NPPs) as they play a vital role in ensuring the overall safety and reliability. This paper discusses the challenges in designing these structures using Finite Element Analysis (FEA) and emphasizes the limitations of the element-based design approach, particularly in areas with complex stress distributions, such as reentrant corners, as well as in proximity to concentrated forces or openings. The paper recommends a member-based design approach where design forces are calculated using section cuts in ANSYS. Critical locations for section cuts are defined and discussed, and the calculation of design forces is illustrated through an example problem. The presented approach aims to enhance efficiency and cost-effectiveness of the design process for engineers working on RC structures in NPPs, while ensuring safety.

INTRODUCTION

RC structures play a crucial role in the overall safety and reliability of NPPs. These structures are designed to withstand various loads (ranging from seismic events to extreme weather conditions) and are vital in preventing the release of radioactive materials in the event of an accident. Ensuring the robustness of RC structures needs a comprehensive analysis of their behavior under various loading conditions, requiring advanced methods such as FEA in the design process.

Analysis Methods in NPP Design

Over the past few decades, FEA method has emerged as an essential tool for seismic analysis and design within the nuclear power industry. FEA offers several advantages for the nuclear industry. First, it enables the analysis of a close representation of complex geometries and different loading conditions that are encountered in NPP structures. Second, it provides detailed information about the stress distribution within the structure. Additionally, FEA allows for parametric studies where different design parameters can be modified and evaluated to optimize the structural design.

As NPPs undergo seismic design, engineers primarily adopt either an element-based or a member-based approach. The former involves the use of finite element stress resultants, specifically element forces and moments per unit width. Meanwhile, the latter, known as the member-based or section-based approach, relies on forces and moments derived at member cross sections or section cuts. The results of FEA, expressed through stress resultants and stress field contour plots, provide a convenient data to identify critical areas for design consideration. However, the element-based design approach has some inherent challenges. It is mesh dependent and tends to be overly conservative in specific locations such as small finite elements, reentrant corners, and areas near concentrated forces or openings.

On the other hand, the forces derived at a section cut offer a solution to these challenges. These forces represent the resultant forces along the member cross section, accounting for the redistribution or

averaging of finite element stresses along the section. This consideration reflects the typical behavior observed in RC members, resulting in a more realistic assessment of structural response. Within this design methodology, the determination of required strengths at section cuts along critical member sections become important. This calculated demand aligns with the principles outlined in ACI 349, which mandates that a structural member "shall be designed to have design strengths at all sections at least equal to the required strengths". Moreover, this approach maintains consistency with code capacity equations, ensuring a design process that is both reliable and in accordance with industry standards. In summary, the member-based approach stands out not only for overcoming challenges associated with mesh dependency and conservatism but also for its capacity to reflect the actual redistribution of forces within an RC structure.

This paper recommends a member-based design approach that uses cuts at specific sections for RC structures. By using this method with ANSYS, the paper offers a practical and efficient guide for engineers working on the design of RC structures in NPPs. Engineers can utilize the provided guidelines identifying critical locations for section cuts. A design example is provided to demonstrate how the member-based approach can be used to optimize the design of structural members and reinforcement.

USE OF SECTION CUTS IN MEMBER-BASED DESIGN

Section cuts in ANSYS are formed by selecting elements on one side of the desired cut and nodes along the cut, and by applying the *FSUM command in Ansys Parametric Design Language (APDL). Section cut forces are calculated by the summation of nodal forces along the cut, with user-defined force summation point, typically the geometric centroid of the section cut.

Section Cuts to Calculate Demand from FEA Models

Section cut forces can be calculated in global or local coordinate systems. In design process, the use of local coordinates is preferred such that the calculated set of forces align with the orientation of the section cut. In slab and wall members, a local coordinate system is used with axes defined in Figure 1. In this configuration, the positive axial load (F1) corresponds to tension in the section cut. Results are presented in the local coordinate system as shown in Figure 1.

F1: Axial load (P)
F2: In-plane shear (V)
F3: Out-of-plane shear (Vz)
M1: Torsional moment (T)
M2: Out-of-plane moment (M)
M3: In-plane moment (Mz)

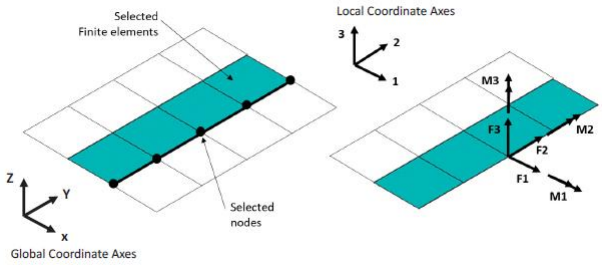


Figure 1. Section cut force resultants in local coordinate system for a slab modeled with shell elements.

Required Strength for Slab and Basemat Design

The design of floor and basemat slabs involves considerations of out-of-plane forces, in-plane diaphragm action, axial loads, and collector forces. Slabs designed for out-of-plane forces, including moment and shear, may exclude axial loads in the flexural design as these loads are primarily due to diaphragm action, involving in-plane flexure and collector forces. Therefore, consideration of axial load is integrated into diaphragm design. However, in the design process, axial loads can be included in the out-of-plane flexural design at discrete section cuts. By determining the axial load at specific section cuts for out-of-plane flexure, especially in areas with significant axial forces, the impact of the in-plane moment is accounted for in the design. This approach eliminates the need for a separate and explicit calculation of in-plane moment.

The effect of diaphragm collector forces on axial load at the end of discontinuous walls is considered in the design by calculating axial load at specific section cuts for out-of-plane moment. Torsional moments increase out-of-plane shear forces, and their effect is included in the design by calculating shear at discrete section cuts, especially in regions with increased shear due to torsion.

In summary, the required strengths for slab and basemat design involve axial load (P) and out-of-plane moment (M) for axial-moment interaction, axial load (P) and out-of-plane shear (Vz) for axial-shear interaction, and in-plane shear (V) for shear and shear-friction at slab-wall interfaces. If axial load is not included in out-of-plane moment design, explicit calculation of in-plane moment and collector forces is necessary.

Guidelines in subsequent sections help determine critical sections for slabs under vertical and lateral loading. Critical section cut locations are approximate and considered the minimum set to obtain demand. Conservatively, section cut lengths for out-of-plane moment and shear should not exceed three times the member thickness, while in-plane shear and moment section cuts extend the entire member depth/length. Additional section cuts, their locations, and lengths can be determined using FEA stress resultants, considering stress distributions due to demands and allowing longer cut lengths when justified by the analysis. In stress resultant contour plots, localized stress concentrations are expected near openings or areas with sharp changes in geometry, but these are not representative as concrete will distribute stresses over a larger region through cracking.

Section Cuts for Out-of-plane Forces – Slab and Basemat

The out-of-plane forces in floor slabs are represented by out-of-plane moment (M) and out-of-plane shear (Vz). These forces are induced by vertical loads such as gravity, buoyancy, and vertical seismic loads, as well as by lateral loads from frame actions, such as seismic forces.

For a slab configuration with four edges fixed, out-of-plane moments due to gravity load exhibit the largest negative moments at support faces and the largest positive moment at the center of the span, with intensity diminishing toward corners. Frame action generates additional moments along the north-south direction, with the highest intensity around the middle of the east-west span. Section cut locations for assessing demands resulting from out-of-plane forces are specified as follows: for out-of-plane moment, they are identified at approximately the center of each slab-wall interface and at a section near the center of the slab's short span (main direction of moment transfer); for out-of-plane shear, the section cut locations are determined at approximately the center of each slab-wall interface. Out-of-plane moments and section-cut locations for out-of-plane moment and shear are illustrated in Figure 2.

Out-of-plane shear forces, concentrated around the center of each slab support, resulting from the distribution of gravity loads to supporting walls. Section cut locations to determine the demand due to out-of-plane forces are established as follows: for out-of-plane moment, around the center of each slab-wall interface and at a section about the center of the slab short span; for out-of-plane shear, around the center of each slab-wall interface. Axial loads are also calculated at these section cuts to account for P-M and P-V interactions in design calculations. Alternatively, axial loads can be included in designing for in-plane moment. ACI 349 permits the calculation of shear force at a distance equivalent to one slab effective depth from the support face, in accordance with the requirements outlined in ACI 318 Section 11.1.3. If not feasible due to finite element mesh constraints, conservative calculation at section cuts defined at the face of the support is acceptable.

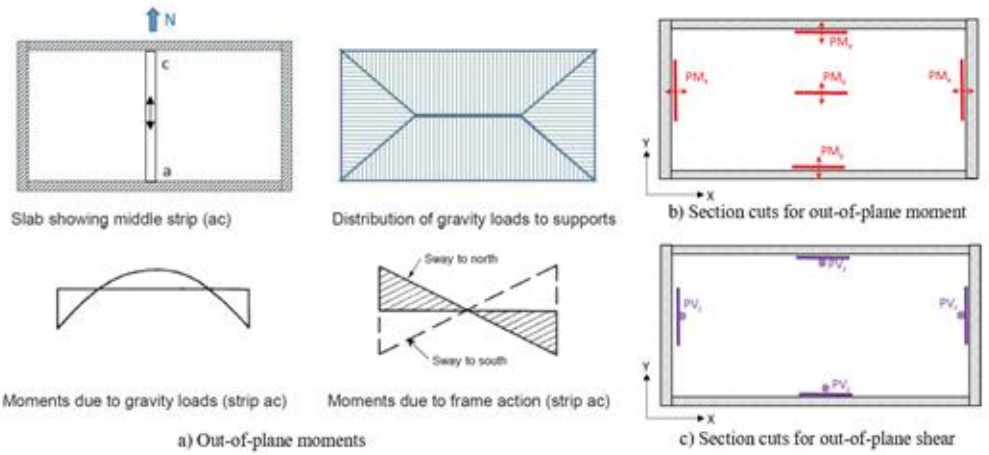


Figure 2. Out-of-plane moments and section cut locations in slabs with four edges fixed.

Considering seismic loads, walls may experience large overturning moments that are balanced by out-of-plane moment and shear in the basemat. Section cuts are required at the ends of walls imposing overturning moments. For a T-shaped wall, the basemat region at the end of the wall flange is subjected to two-way shear. The calculation of out-of-plane shear demand in the basemat is performed conservatively, assuming the wall axial load is concentrated in an area with dimensions equal to the wall thickness (b_w). Outside this region, where one-way shear occurs, section cuts are defined at a distance of one basemat effective depth (d) from the wall's face. The section cut locations for one-way and two-way shear in basemat are shown in Figure 3. Section cut locations for out-of-plane bending due to wall overturning are determined based on recommendations, limiting the cut length to three times the basemat thickness.

Section Cuts for In-plane (Diaphragm) Forces – Slabs

In-plane forces in a diaphragm structure involve in-plane moments, chord forces, in-plane shear, and shear transfer or collector forces. A simple diaphragm as shown in Figure 4, supported by walls at its four edges and subjected to seismic forces, can be conceptualized as a horizontally simple supported beam. In-plane moment and shear diagrams illustrate forces distributed across the diaphragm depth (d), with depth being the dimension parallel to seismic forces, and span being the distance between walls resisting these forces.

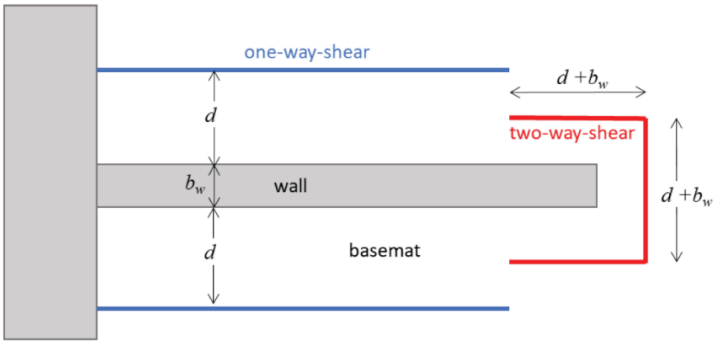


Figure 3. Section cut for one-way and two-way shear in basemat subject to wall overturning.

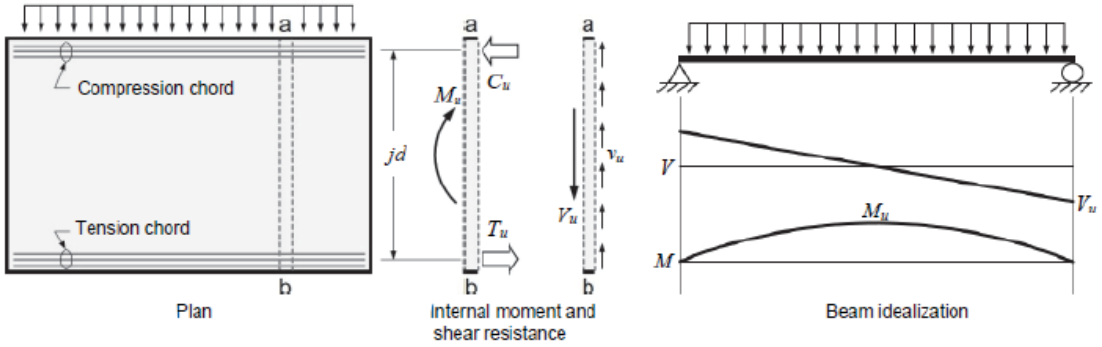


Figure 4. In-plane moment and shear at section cut ab, in a diaphragm supported by two walls at its ends (NEHRP Seismic Design Technical Brief No. 3).

Chord forces play a crucial role in counteracting in-plane moments, creating compression and tension couples at both the upper and lower edges of the diaphragm. The peak chord forces occur at the mid-span, corresponding to the location of the maximum in-plane moment. Simultaneously, the highest in-plane shear forces appear at the diaphragm supports, specifically the walls. To evaluate the demand for in-plane moment and shear, section cuts are located at regions perpendicular to the diaphragm edges and along the diaphragm supports. For chord forces, these cuts occur about the middle of diaphragm edges due to seismic forces that act perpendicular to each edge. In contrast, for in-plane shear, section cuts are set at the diaphragm supports (walls). Section cut locations also play a crucial role in considering out-of-plane moment and axial load interactions for section design.

When the supporting wall is not continuous across the diaphragm depth, a portion of the diaphragm shear force is transferred directly to supporting walls, while the remaining portion is handled through collector elements involving compression and tension forces. Maximum collector forces occur at the ends of discontinuous walls. Section cut locations for evaluating collector forces and out-of-plane moments are critical, considering P-M interaction.

Section Cuts for Forces around Openings - Slabs

The design considerations for slabs with openings involve specific guidelines for small and large openings. Small openings, typically less than one or two slab thicknesses, are not required to be modeled. However, for larger openings, the slab must be designed to efficiently transfer forces around the openings.

As illustrated in Figure 5, in the case of a sample slab with a large opening at the center and subjected to both gravity load and seismic forces along the north-south direction, load transfer around the opening is crucial for both gravity and frame action. The blue double-head arrows in Figure 5 show the direction of load transfer and out-of-plane moments around the opening. Calculations for out-of-plane moments and shear around openings are required at specified section cut locations around the corners of the opening. Additionally, the in-plane axial forces must be determined at the section cut locations to facilitate design evaluations, considering P-M and P-V interactions.

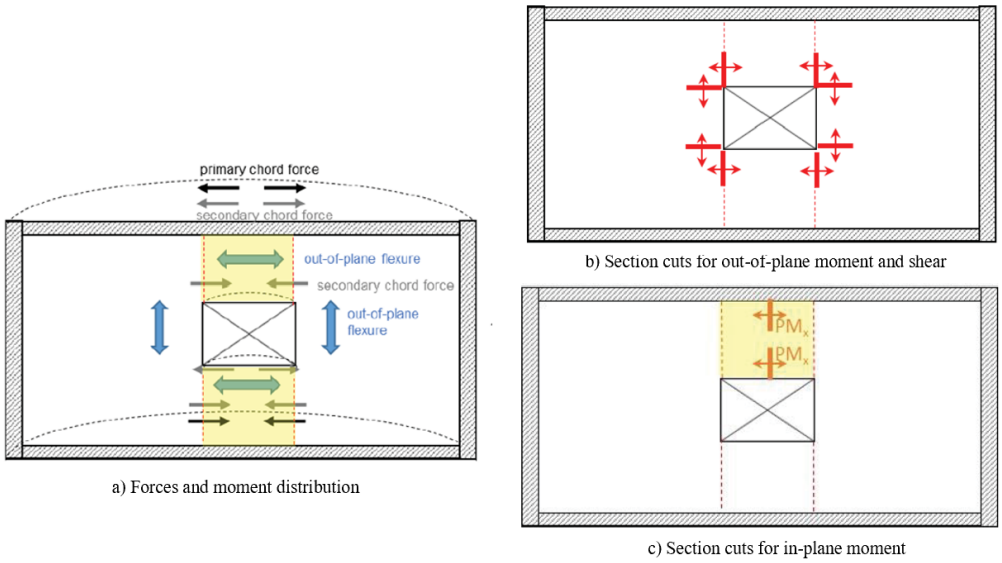


Figure 5. Slab with large opening: Forces and moment distribution along with section cuts.

Concerning in-plane forces, the in-plane bending of small diaphragm segments on each side of the opening generates additional chord forces. For seismic motion in the north-south direction, yellow shaded areas on the north and south sides of the opening represent active diaphragm segments, with a similar configuration for east-west seismic motion.

Figure 5 outlines two types of chord forces: primary chord forces resulting from in-plane bending of the entire slab and secondary chord forces arising from in-plane bending of diaphragm segments above and below the opening. Both primary and secondary chord forces at the top and bottom slab edges are additive. Considering the global and local response behavior, the calculation of chord forces for the north diaphragm segment is essential at specified section cut locations for seismic forces in the north-south direction. Similar considerations apply to the south diaphragm segment and the east and west diaphragm segments for seismic motion in the east-west direction. Section cut locations are critical for calculating out-of-plane moments to evaluate section design, considering P-M interaction. Alternatively, if axial load is not considered in out-of-plane moment design, in-plane moment calculations are required at a section cut crossing the diaphragm depth.

Required Strength for Walls

Structural walls play a crucial role in resisting in-plane shear and in-plane moment, with consideration for out-of-plane forces such as out-of-plane flexure and out-of-plane shear, similar to slab design. In low gravity load situations, such as those in safety-related structures with massive walls, axial loads are primarily caused by in-plane flexure due to lateral loads. This requires calculating the axial load by determining the in-plane moment at critical section cuts.

Efficiency in the design process is achieved by incorporating the total axial load in the out-of-plane flexural design through P-M interaction. Explicit calculation of in-plane moment is required in specific cases, including sections at the base of the wall and where wall boundary elements or special transverse reinforcement are needed.

Torsional moments (T) increase the out-of-plane shear force (Vz). Consequently, calculating the out-of-plane shear at discrete section cuts, considering critical member regions and areas with increased shear due to torsion, includes the effect of the torsional moment in the design process.

In summary, the required strengths for wall design involve considering axial load (P) and out-of-plane moment (M) for axial-out-of-plane moment (P-M) interaction, axial load (P) and out-of-plane shear (Vz) for axial-out-of-plane shear (P-Vz) interaction, in-plane shear (V) for shear and shear-friction at slab-wall interfaces, and in-plane moment (Mz) and axial load (P) for verifying in-plane moment capacity at wall sections, including perpendicular walls, and assessing the need for boundary elements.

Critical section cut locations are determined for gravity and lateral loading. Conservatively, the section cut length for out-of-plane moment and out-of-plane shear should not exceed three times the member thickness. Section cut locations and extensions can also be determined based on FEA stress resultants, allowing flexibility beyond the three times member thickness.

Section Cuts for Out-of-plane Forces - Walls

Wall panels supported on all four edges by floor slabs or perpendicular walls exhibit behavior comparable to slabs when subjected to out-of-plane forces. Specifically, for out-of-plane moments, the critical locations are approximately at the center of each slab-wall interface and at a section around the midpoint of the wall's short span, aligning with the primary direction of out-of-plane moment transfer. As for out-of-plane shear, the relevant section cuts are located at the center of each slab-wall interface.

Section Cuts for In-plane Forces - Walls

Seismic forces transmitted from floor slabs induce in-plane shear on walls, with higher elevations experiencing gradually increasing forces. For squat cantilever walls, common in NPPs, the primary in-plane shear and moment occur at the wall base, although wall embedment can change this distribution. Therefore, the evaluation of in-plane shear and moment requires section cuts at the base of walls at each story. In one-story cantilever walls, in-plane moment equilibrium is achieved through compression and tension couple or chord forces at wall boundaries. Section cuts for in-plane shear and chord forces are defined by including portions of perpendicular walls. Out-of-plane moment calculations are required at section cut locations for chord forces that do not include parts of perpendicular walls. A confirmatory check is essential, verifying that the in-plane moment demand does not exceed the calculated capacity, considering all longitudinal reinforcement, as large axial forces near wall boundaries can increase in-plane moments.

Section Cuts for Forces Around Openings - Walls

In the design of structural walls with openings, consideration is given to the treatment of forces around these openings. Small openings, approximately one or two wall thicknesses, are not a significant concern, as discussed previously for slabs. For larger openings, the design involves the transfer of forces in accordance with ACI 349 guidelines. Walls with openings consist of both vertical and horizontal segments, as shown in Figure 6, where vertical segments transfer shear forces between wall portions above and below. Additional section cuts are placed at the base of vertical wall segments to calculate in-plane shear and chord forces.

Horizontal wall segments, like beams, transfer shear forces horizontally from one end to the other. Section cuts are added at each end of horizontal wall segments to calculate in-plane shear and chord forces. A confirmatory check is imperative, verifying that the in-plane moment demand obtained at the section cuts for in-plane shear is below the capacity calculated considering all longitudinal reinforcement. Out-of-plane

forces around openings follow a similar approach as outlined for slabs. The section cuts for calculating out-of-plane moment and out-of-plane shear are located around an opening in a wall.

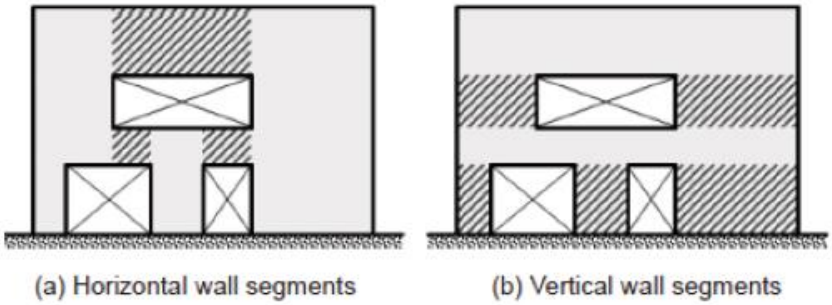


Figure 6. Vertical and horizontal wall segments (Moehle et al. (2011)).

Determination of Section Cut Locations Using FEA Stress Resultants

The determination of critical section cut locations in slabs and walls involves analyzing contour plots of FEA stress resultants which are calculated for each load combination, including seismic forces. Peak FEA stress resultants due to seismic loads are obtained through response spectrum or time history analysis, considering motion in three directions. The seismic and non-seismic stress resultant sets are then combined. These resultants are crucial in understanding structural behavior. The local coordinate system alignment with longitudinal reinforcement directions is essential, with consideration given to the sign convention used by the ACI. The FEA stress resultants, per unit length, are shown in Figure 7 in the finite element local coordinate system.

Section cut locations and lengths are determined by analyzing contour plots corresponding to specific demand types (e.g., in-plane shear, axial load, out-of-plane moment, and shear). The peaks in these plots indicate critical regions where section cuts should be placed, and the lengths are based on the size of these regions. Section cut lengths should generally not be less than three times the slab thickness, except where stress resultants change sign or are limited by openings. Additionally, for in-plane shear and in-plane moment, the section cut should extend the entire member depth or length. Finally, calculations for out-of-plane moment, out-of-plane shear, P-M demand, and P-Vz demand are also recommended at locations of significant tension for a comprehensive analysis.

- N11, N22: membrane axial forces
- N12: membrane shear force
- M11, M22: out-of-plane moments
- M12: twisting moment
- Q13, Q23: out of plane shear forces

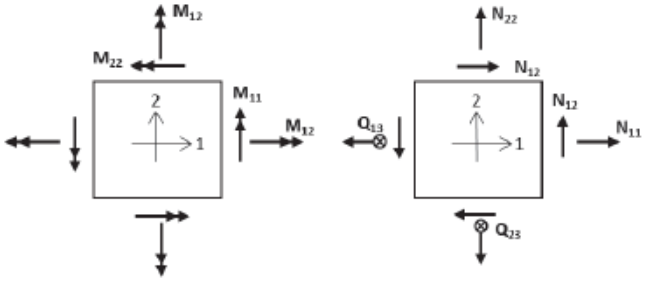


Figure 7. Finite element stress resultants in their local coordinate system as output in ANSYS.

DESIGN EXAMPLE

This section illustrates the practical application of defining section cuts using the discussions and guidelines provided in the previous sections on an example building. The focus is on illustrating how section cuts are defined according to the provided guidelines and confirmed using the FEA stress resultants.

The example RC building is a box-type structure that represents the configuration, load path, and redundancy within a typical building in NPP. The building is modeled in ANSYS using solid shell (SOLSH190) elements as illustrated in Figure 8. It includes RC walls with a thickness of 2.5 ft. The roof is a 2.5 ft thick RC slab with a 15 ft square hole at the south-west corner. Additionally, there are two interior walls running in the north-south direction, positioned at the midsection along the east-west direction. The design example focuses on the west wall which features a 15 ft square hole around the center.

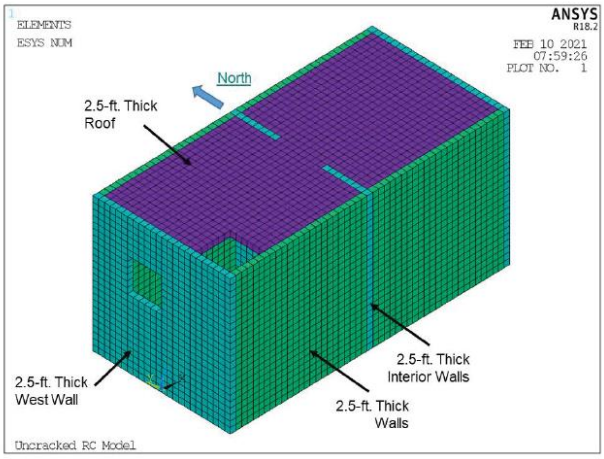


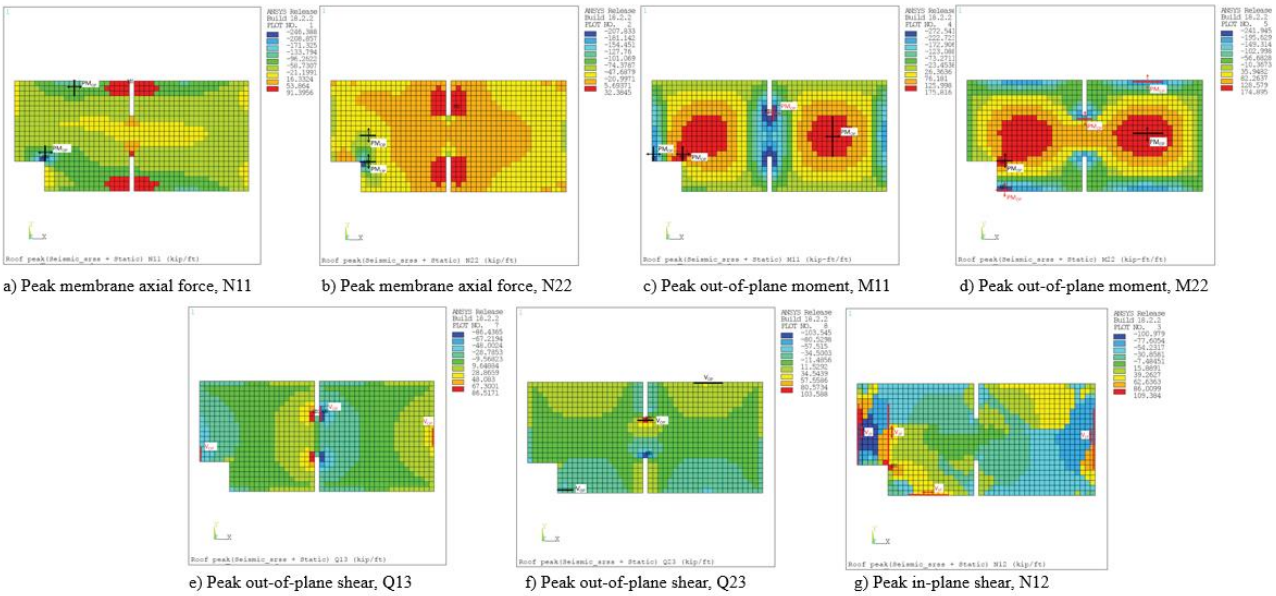
Figure 8. Box-type example building.

Stress Resultants

The distribution of element-based stress resultants is presented in Figure 9 for the roof and Figure 10 for the west wall. For the roof elements, the local axis 1 aligns with the X-axis, while local axis 2 aligns with the Y-axis. For the west wall elements, local axis 1 corresponds to the Y-axis, and local axis 2 aligns with the Z-axis. The critical section cut locations, essential for calculating the required strengths in both out-of-plane and in-plane directions, are also shown in the figures. The location of section cuts based on the established guidelines aligns effectively with the location of peak stress results observed in the contour plots shown in Figure 9 and Figure 10, ensuring that the selected set of section cuts accurately represents the critical regions in the structural members.

Calculation of Design Demands at Section Cuts

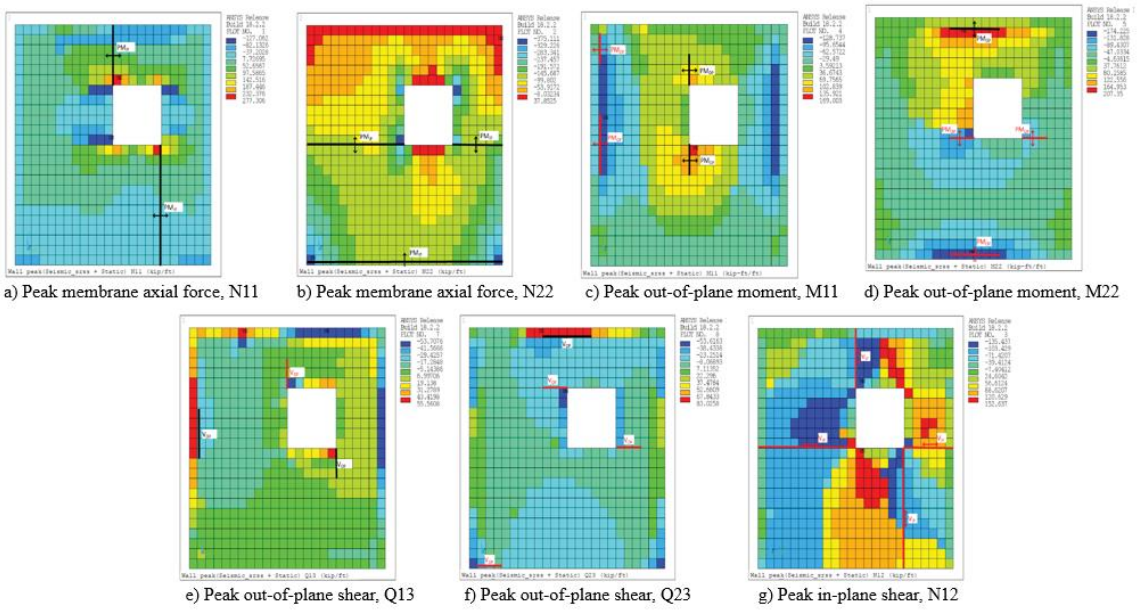
The location and the length of the required section cuts for each demand type are presented in Figure 11 for the roof slab and the west wall. These figures include a total of 23 section cuts for the roof slab and 17 for the west wall to be employed in the design process. It is important to note that out-of-plane demands, including out-of-plane moment and shear, are calculated at section cuts labeled with names starting with "m," while in-plane demands, comprising in-plane moment and shear, are obtained at section cuts with names starting with "v." Figures 12 and 13 also show the final reinforcement calculated based on the selected section cuts for the roof slab and west wall, respectively.



a) Peak membrane axial force, N11 b) Peak membrane axial force, N22 c) Peak out-of-plane moment, M11 d) Peak out-of-plane moment, M22

e) Peak out-of-plane shear, Q13 f) Peak out-of-plane shear, Q23 g) Peak in-plane shear, N12

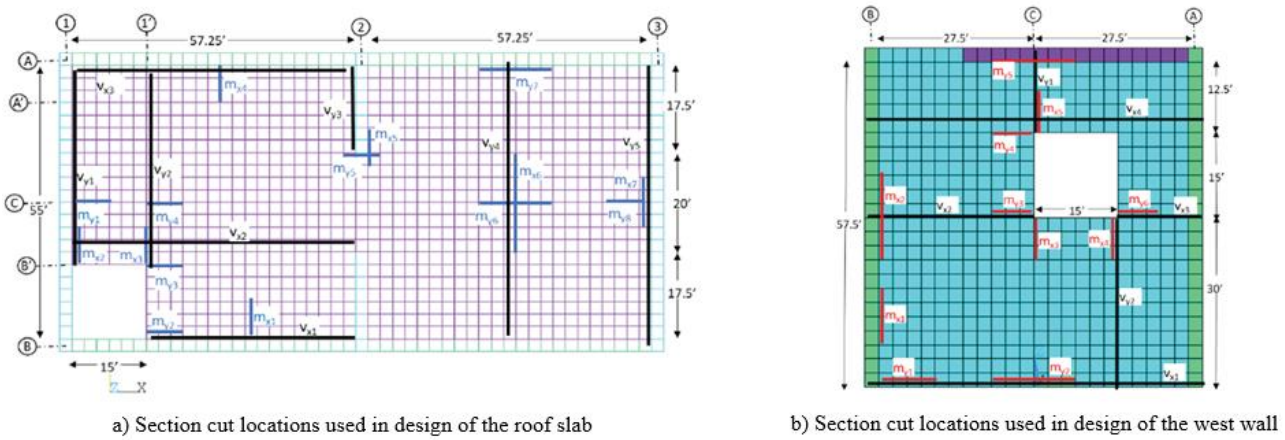
Figure 9. Stress resultants – roof slab.



a) Peak membrane axial force, N11 b) Peak membrane axial force, N22 c) Peak out-of-plane moment, M11 d) Peak out-of-plane moment, M22

e) Peak out-of-plane shear, Q13 f) Peak out-of-plane shear, Q23 g) Peak in-plane shear, N12

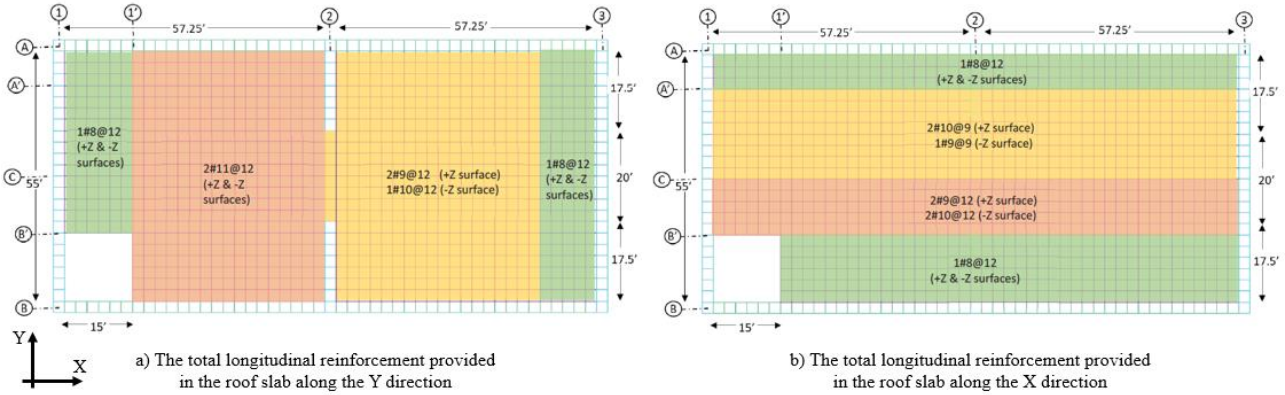
Figure 10. Stress resultants – west wall.



a) Section cut locations used in design of the roof slab

b) Section cut locations used in design of the west wall

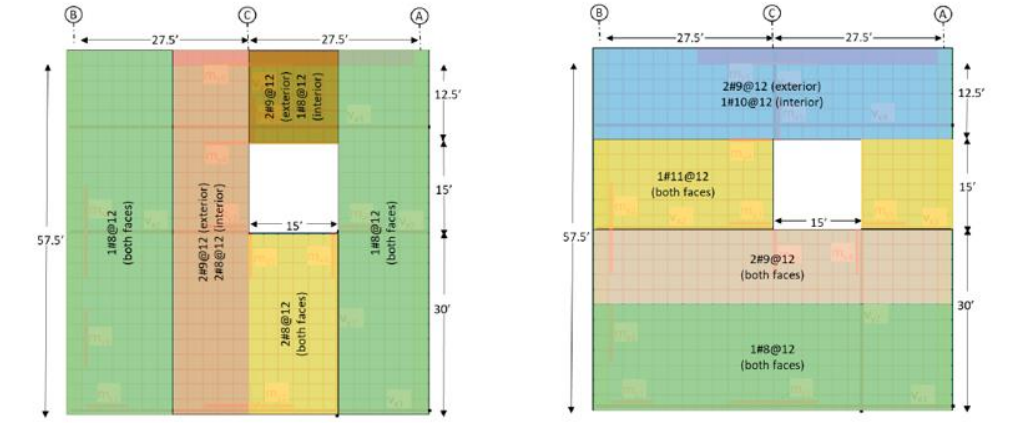
Figure 11. Section cut locations.



a) The total longitudinal reinforcement provided in the roof slab along the Y direction

b) The total longitudinal reinforcement provided in the roof slab along the X direction

Figure 12. Total reinforcement for the roof slab.



a) Total provided vertical reinforcement for the west wall

b) Total provided horizontal reinforcement for the west wall

Figure 13. Total reinforcement for the west wall.

CONCLUSIONS

Different methods in calculating forces for design of members in NPP are discussed. Specifically, the element-based and member-based design approaches are described, emphasizing the advantages of the latter in overcoming mesh dependency and conservatism of the former. The implementation of member-based design using section cuts in ANSYS is outlined in detail.

The paper provides a comprehensive guideline for engineers working on the design of RC structures in NPPs to identify critical section cut locations in RC slabs, basemat and walls, and with considerations of openings. These guidelines are essential for accurately capturing demands for different design and loading conditions.

The member-based design approach with guidance on defining the location of section cuts, as presented in this paper, offers a more rational representation of RC behavior and a practical solution for engineers involved in analyzing and designing of complex RC structures in NPPs. The recommended methodology contributes to the ongoing efforts in ensuring the safety and reliability of critical structures within nuclear facilities.

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