Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025
Division VI

ON THE AVERAGING OF DEMANDS FOR STRUCTURAL ELEMENTS IN SAFETY-RELATED NUCLEAR FACILITIES

Shubham S. Gyawali[1], Taha Al-Shawaf[2], Saahastaranshu R. Bhardwaj[3]

[1]PhD student, The University of Alabama, Tuscaloosa, AL, USA (ssgyawali@crimson.ua.edu)
[2]Technical Consultant, Orano Federal Services, Charlotte, NC, USA (taha.alshawaf@orano.group)
[3]Principal Research Engineer, Purdue Applied Research Institute, West Lafayette, IN, USA (saahas.bhardwaj@gmail.com)

ABSTRACT

Labyrinthine walls (reinforced concrete or steel-plate composite (SC)) in safety-related nuclear facilities need to be designed for eight internal demands acting simultaneously: three in-plane normal & shear forces, two out-of-plane moments, one torsion moment, and two out-of-plane shear forces. AISC N690 provides the guidelines to simulate the SC wall as an equivalent linear elastic finite element (LEFE) model where elements of the wall such as connectors (studs, ties), steel plates, and the interaction between different elements are not explicitly modeled. This design approach is computationally efficient. The eight demand types for each element obtained from the LEFE analysis need to be checked against the strength provisions in AISC N690. However, the LEFE models may show significant stress concentrations at corners and openings. Additionally, since the LEFE models do not explicitly capture phenomenon such as steel yielding and redistribution of stress, the stress concentrations may not be realistic. To address this challenge, AISC N690 permits the averaging of demands. While AISC N690 mentions the regions over which averaging can be done, it does not describe how the averaging needs to be done. ACI 349 is silent on the topic of averaging of demands for walls in nuclear facilities. This paper presents an exploratory study into the topic by using two methods of averaging. The methods are: (a) smear averaging of demands of all elements occupying the panel area, (b) averaging of demands of the elements along the edges only to produce the specific force and moments along that edge. To validate these methods, Non-linear inelastic finite element (NIFE) and LEFE models were developed, and demand-to-capacity ratios (DCRs) were calculated. A sample case for in-plane shear force demands was evaluated. Contour plots of DCRs were constructed for both NIFE and LEFE models at load corresponding to the peak load for NIFE model (force capacity, FC). Also, a contour plot of DCRs was constructed for the LEFE model at the displacement corresponding to that of the NIFE model at peak load (displacement at inelastic model capacity, DIMC). The values from the LEFE FC plot matched reasonably well with that of the NIFE model. Both methods of averaging were performed for all the elements in the wall to provide detailed observation for three sample regions. The developed FE models will be used to evaluate the effectiveness of the two averaging approaches for multiple loading scenarios.

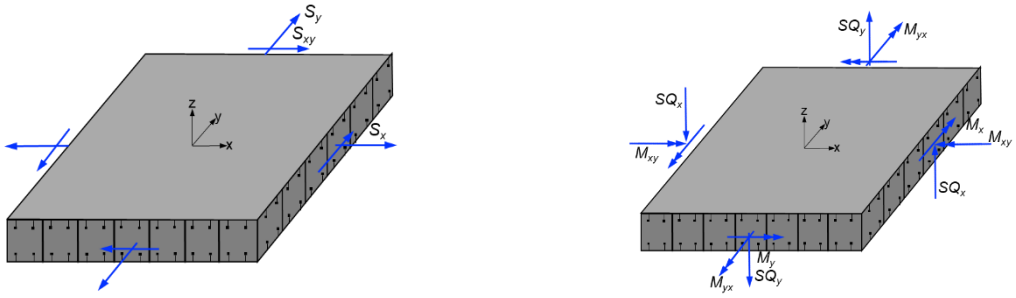
INTRODUCTION

SC walls are characterized as having plain concrete wall sandwiched between steel plates. The plates are connected together through ties and composite action between steel and concrete is achieved through the use of steel anchors and/or ties (Bhardwaj and Varma, 2017). According to Coronado et al. (2009), it is efficient to use shell and plate elements in the finite element structural analysis of these structures. The element forces and moment obtained from the analyses can be used by the structural engineer as demands in the design process. For shell model, the internal design demands are a set of eight internal demands (Figure 1) acting simultaneously which include three in-plane forces (S_x, S_y, S_{xy}), two out-of-plane moments (M_x and M_y), one torsional moment (M_{xy}) and two out-of-plane shear forces (SQ_x, SQ_y). For calculating these demands, AISC N690 (AISC 2018) provides guidelines according to which a calibrated linear elastic

finite element (LEFE) model of the SC walls can be developed. But the LEFE model does not consider the presence of some elements of the wall such as connectors (steel headed studs and ties) and their interaction with concrete and steel plates and the interaction between steel plates and concrete. Additionally, the LEFE model uses an equivalent linear elastic material (AISC N690, AISC 2018). The model thickness, elastic modulus, and Poisson's ratio are calibrated to match the effective stiffness of the model with the cracked stiffness values per AISC N690.

FE analyses may indicate stress concentration in elements near connection region or near discontinuities (openings for pipes, doors, etc.). These stress concentrations can amplify if finer mesh size is used. AISC N690 (AISC 2018), Appendix N9, defines a panel for SC wall over which the averaging of the demands can be performed. Since force transfer between walls occurs at the connection region and the anchorage to the base foundation, for design consideration AISC divides the wall into interior region and the connection region. The recommended panel size for averaging (over the expanse of which averaging is allowed) is t_{sc} x t_{sc} for connection region and regions around openings whereas it is $2t_{sc}$ x $2t_{sc}$ for interior region, where t_{sc} is the thickness of the wall. For example, for a 2 ft. thick wall, the demands in an element in the connection region can be averaged over the panel size of 2 ft. x 2ft surrounding it. However, the N690 code does not provide the procedure for averaging the demands. Even ACI 349 (2013) code does not provide any guidance regarding averaging of these demands and the associated regions for averaging. The purpose of this paper is to illustrate the use of two potential averaging methods for structural elements in safety-related nuclear facilities utilizing commercially available finite element software, ABAQUS (Dassault, 2023). The methods are illustrated using a sample loading case of in-plane shear. Future work will include using the developed FE models to evaluate the effectiveness of the averaging approaches for multiple loading scenarios as discussed in AISC Steel Design Guide 32 (Bhardwaj and Varma, 2019) and Sierra et al. (2023). The methods considered in this paper are:

1. Smear averaging which means averaging of all the demands of all the elements occupying the panel area, option A.
2. Averaging of demands of the elements along the edges only to produce the specific forces and moments along that edge only, option B.



a) In-plane forces b) Out of plane forces and moments

Figure 1. Demand types of SC panels in safety related structures (adapted from Bhardwaj et al., 2017)

DIMENSIONS AND PARAMETERS OF THE SAMPLE WALL

Based on design specifications provided by Appendix N9 of ANSI/AISC N690 (AISC, 2018) and AISC Steel Design Guide 32 (Bhardwaj and Varma, 2019), an internal SC wall was selected as an example problem. Since the focus of this paper is on the effectiveness of different methods of averaging and nature of stress concentrations around openings, simplified standalone SC shear wall (details shown in Figure 2) was selected with an understanding that its behavior will be different than labyrinthine SC wall structure.

However, the methods developed in this paper can also be evaluated for labyrinthine SC walls. The thickness of the concrete portion of the wall is 24 inches and faceplate thickness is taken as 0.5 inches. Thus, the steel plate reinforcement ratio is 0.04 which is less than the maximum reinforcement ratio criteria (0.05) and greater than the minimum reinforcement criteria (0.015) specified in the specification. The height and width of the wall was kept as 40 feet. A typical opening, representing an HVAC duct opening, with dimensions of 3 ft width by 2 ft height was considered at 6 feet away from the edges. An equipment transfer door of 16 ft width and 20 ft height was located at one edge of the wall. These typical openings would enable the evaluation of the nature of stress concentration and large plastic strains in faceplates. The studs of ¾ in. diameter were used at the spacing of 1 foot on the faceplates and two faceplates were connected to each other using ties of ¾ in. diameter with spacing of 24 inches in both directions. The yield stress for studs and ties is 65 ksi. The yield stress of steel plates is 57 ksi and the compressive strength of concrete is taken as 6 ksi.

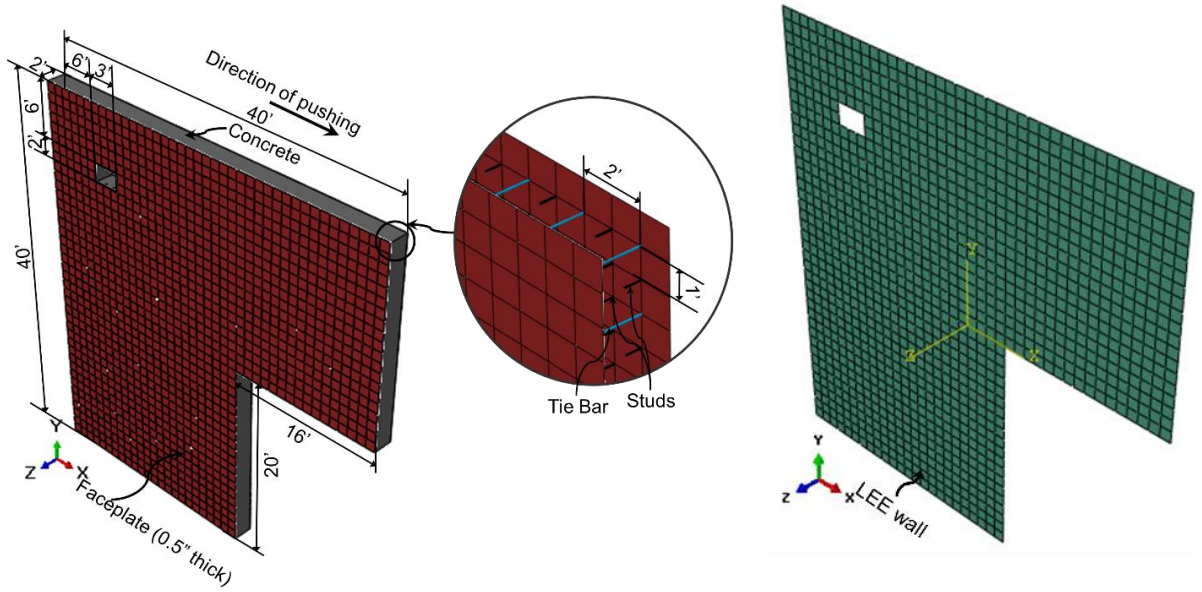
DEVELOPMENT OF FINITE ELEMENT MODELS

Finite Element models were developed using ABAQUS (Dassault, 2023). Two models were developed: (a) Non-linear Inelastic Finite Element (NIFE) model (detailed model where all elements, i.e., faceplate, concrete infill, ties and studs, are explicitly modeled), and (2) Equivalent Linear Elastic Finite Element (LEFE) model.

(1) Non-linear Inelastic Finite Element (NIFE) Model: The 3D representation of the model, including pertinent dimensions, is shown in Figure 2a. The steel stress-strain behavior was modeled based on measured properties by Bhardwaj et al. (2023). The uniaxial compression stress-strain behavior of concrete was defined using the modified Popovic's empirical stress-strain model recommended by Collins et al. (1992). The uniaxial tension strength and the post-peak behavior are defined using the equations for plain concrete provided in CEB-FIP Model Code (1990).Concrete material behavior was modeled as elastic with brittle cracking whereas steel plates, ties, and studs were modeled as elastic-plastic considering strain hardening effect (3-5% of elastic modulus). The concrete infill was represented using C3D8R (eight-node linear brick, reduced integration, hourglass control) elements. All steel plates were modeled as S4R (four-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) elements. Studs and ties were modeled as B31 (two-node linear beam in space) elements, with both the tie bars and shear studs embedded in the concrete. To simulate the behavior of the connections, the force-slip relationship for the connector elements, as provided by Ollgaard et al. (1971), was used. Cartesian-type connector elements were used to define the force-slip behavior between studs and steel plates, enabling an accurate representation of the interaction. Normal and tangential contact interactions given by ABAQUS (Dassault, 2023) were established between all components to account for their interaction during loading. The bottom of the wall section was fixed, and the symmetry boundary conditions were applied on the other three sides to simulate the internal wall structure. X symmetry was applied on the top of the wall meaning displacement degree of freedom in X-direction and rotation degrees of freedom in Y and Z directions were restrained. Similarly, Y symmetry was applied on other two sides implying displacement degree of freedom in Y-direction and rotational degrees of freedom in X and Z directions were restrained. A reference point was defined at the top of the wall which was given a rigid constraint with respect to the top section of the wall. The in-plane displacement was applied to this reference point. The element size used for this model was 12 in. x 12 in., half the wall thickness. The structure was subjected to in-plane loading by using displacement control method. Pushover failure analysis was conducted to initiate the yielding of any element of the steel plate. Since the displacement was applied at the top of the wall and no flange walls were modeled, the steel plates in the wall buckled in compression at the base of the wall. The in-plane behavior of the walls was not shear dominated as would be the case for

labyrinthine walls. The modeled wall experienced a combination of in-plane shear and in-plane flexure stresses (Bhardwaj et al., 2019).

(2) Equivalent Linear Elastic Finite Element (LEFE) model was developed using calibrated thickness, Poisson's ratio, and elastic modulus values to match the model stiffness with the recommended stiffnesses per AISC N690 (AISC 2018). The equivalent thickness of the wall section was calculated to be 35.01 inches, elastic modulus was calculated as 1714.98 ksi and the Poisson's ratio of concrete (0.17) was used. The wall section shown in Figure 2b was modeled using S4R (four-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) elements. The boundary conditions and method of application of loads were consistent with NIFE model. To be consistent with NIFE model, the element size for this model was also set to 12 in. by 12 in.



a) NIFE model (concrete removed in inset picture for better view)

b) LEFE model

Figure 2. Models used in the analysis.

RESULTS AND DISCUSSION

A sample result for in-plane shear force is presented in this section. The in-plane shear strength of the section was calculated based on AISC N690 (AISC 2018) as 585 kips/ft. The peak base shear (FC) in the NIFE model and the corresponding displacement (DIMC) were noted. The stress states in the LEFE models at this force (FC) and displacement values (DIMC) were compared with that for the NIFE model. The LEFE model demands at FC and DIMC were averaged using the two approaches mentioned previously. Figure 3 shows the demand to capacity ratio (DCR) for in-plane shear forces for NIFE model at the peak load (FC). The maximum DCR obtained for this condition was 1.06. This was found to be at the bottom of the wall where all the degrees of freedom were fixed. The minimum DCR was found to be -0.31 on the top left corner of the wall. Similarly, the DCR plots were obtained for LEFE model at FC (Figure 4) and at DIMC (Figure 5). The maximum DCR obtained for LEFE model at FC was 1.07 near the connection region whereas the minimum DCR was found to be -0.06 at the other edge of the wall. The stress patterns observed

in these figures will change if the direction of loading is reversed. The overall LEFE stress state at FC (Figure 4) is comparable with that for NIFE model (Figure 3). However, the DCR plot for LEFE model at DIMC (Figure 5) is significantly higher than that for NIFE, with the maximum DCR being 2.46 and minimum being -0.15. This indicates that the LEFE model stiffness becomes significantly higher than the that for the NIFE model as the NIFE model reaches its peak loading (because of concrete cracking, steel yielding and buckling in the NIFE model).

Two methods of averaging were used for the LEFE model demands. They were a) smear averaging meaning averaging of demands of all elements occupying the panel area, and b) averaging of demands along the edge elements only to get the demand. Three sample regions, labeled as Region A, Region B, and Region C in Figures 3, 4, and 5 were considered to illustrate the use of the averaging methods. Since the element size is $t_{sc}/2$, the panel size for connection regions was considered to be $1.5t_{sc}$ (to include whole elements in the panel section; Regions A and B in Figures 3, 4, and 5). Similarly, a panel size of $2.5t_{sc}$ was considered for averaging in the interior regions (Region C in Figures 3, 4, and 5). While averaging, elements with negative DCR were not considered.

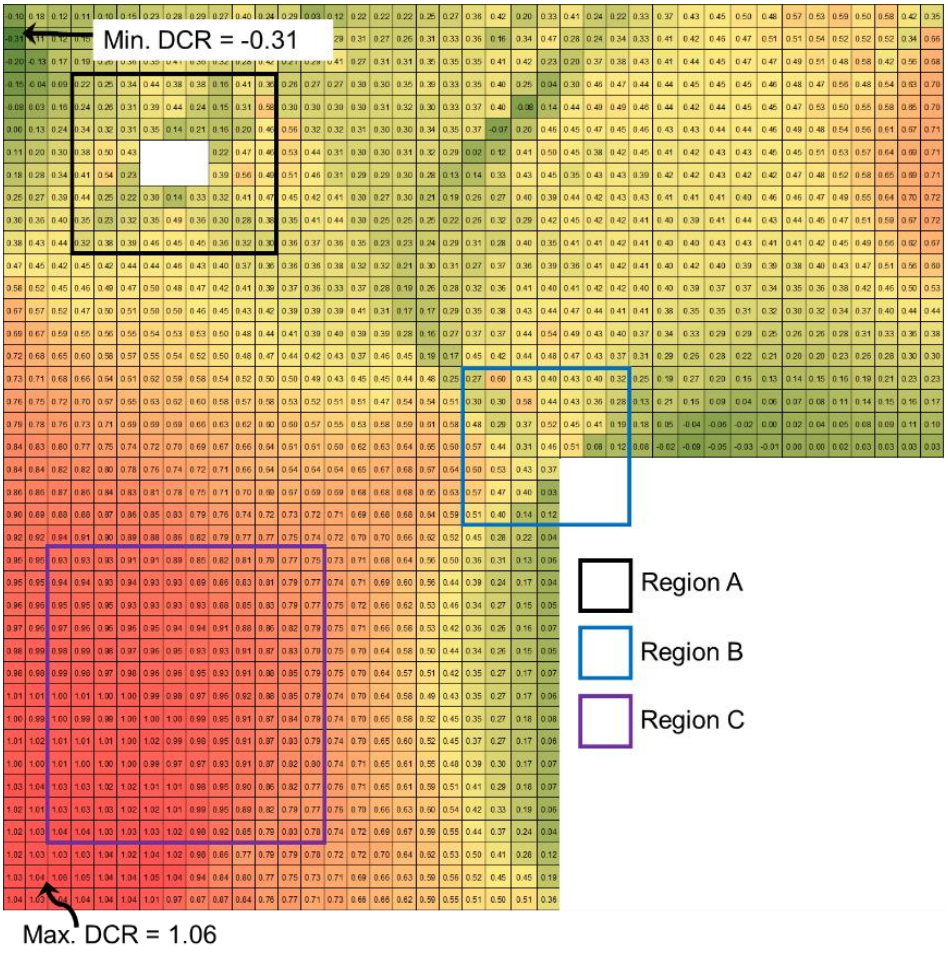


Figure 3. In-plane shear Demand Capacity Ratios (DCRs) for Non-linear Inelastic Finite Element (NIFE) model at its peak load (FC, DIMC).

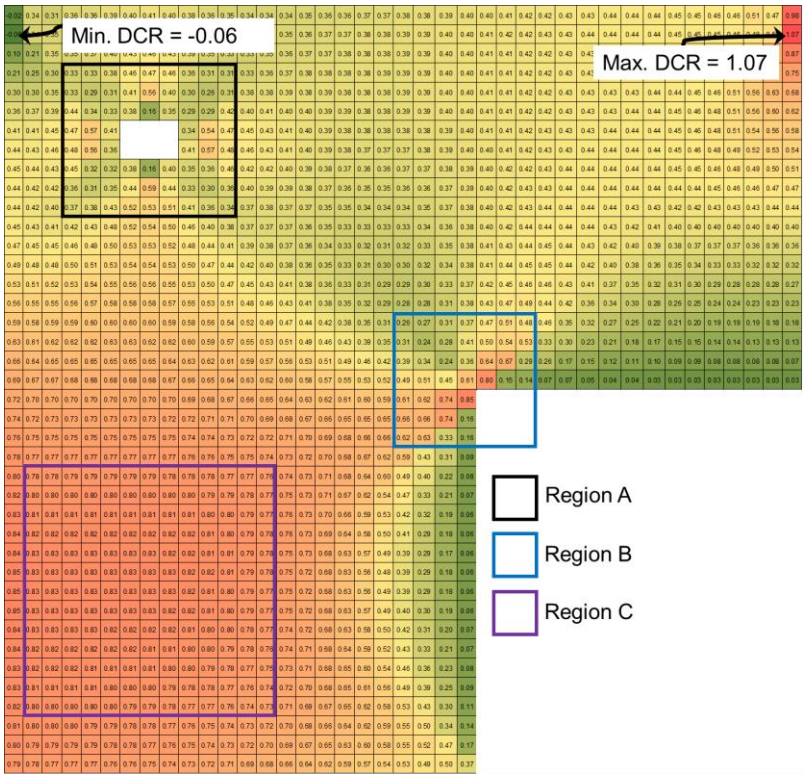


Figure 4. In-plane shear DCRs for Linear Elastic Finite Element (LEFE) model at base shear magnitude equal to the peak force of the NIFE model (FC)

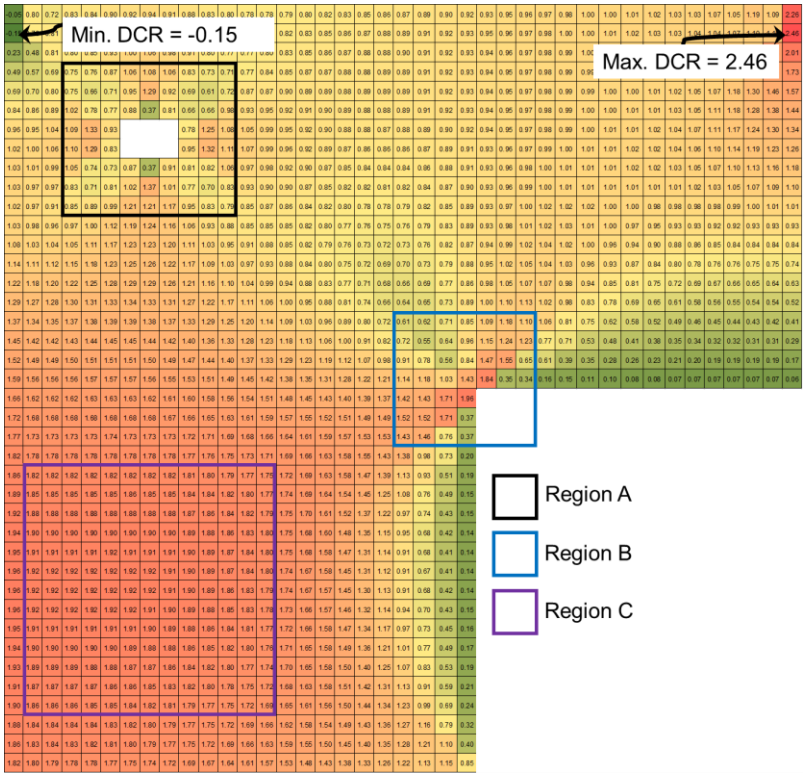
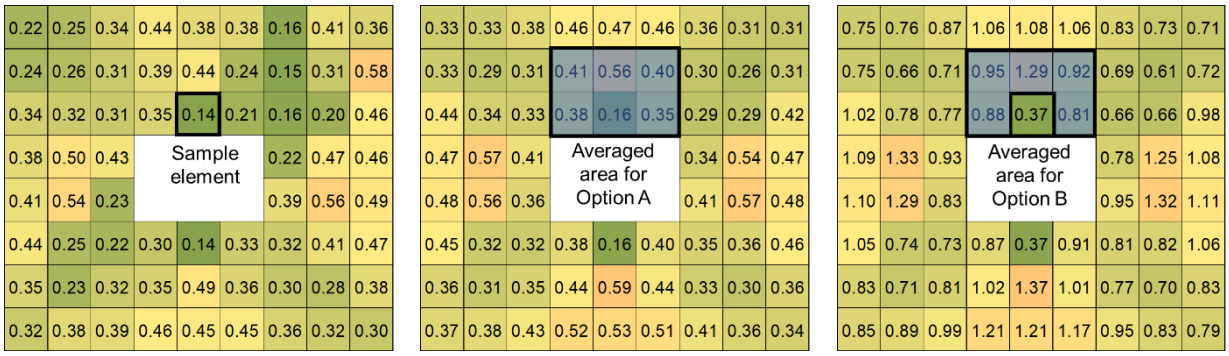
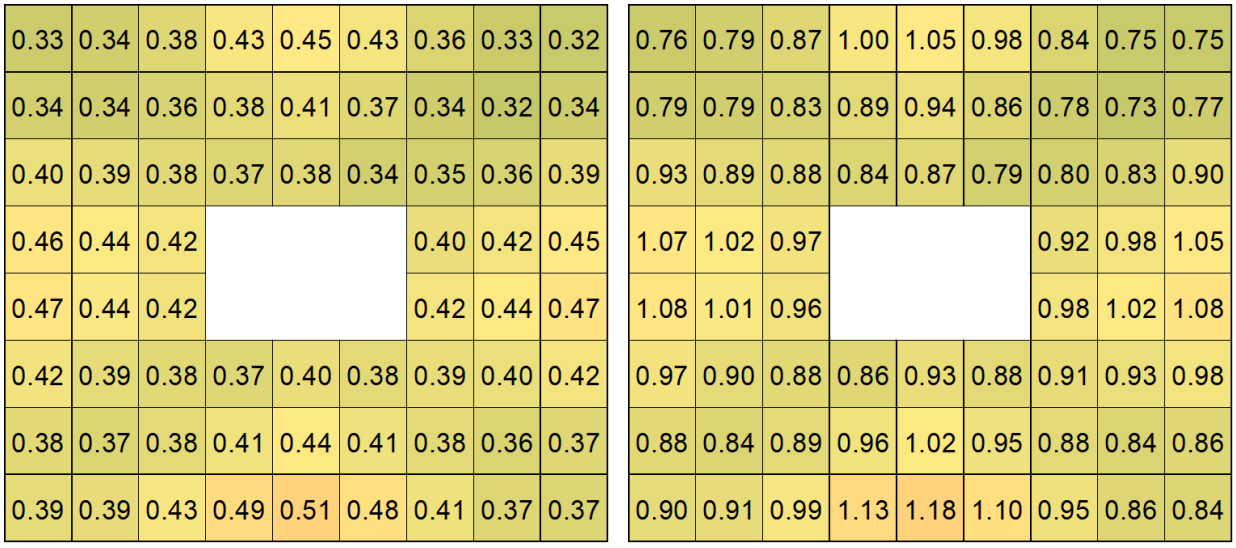


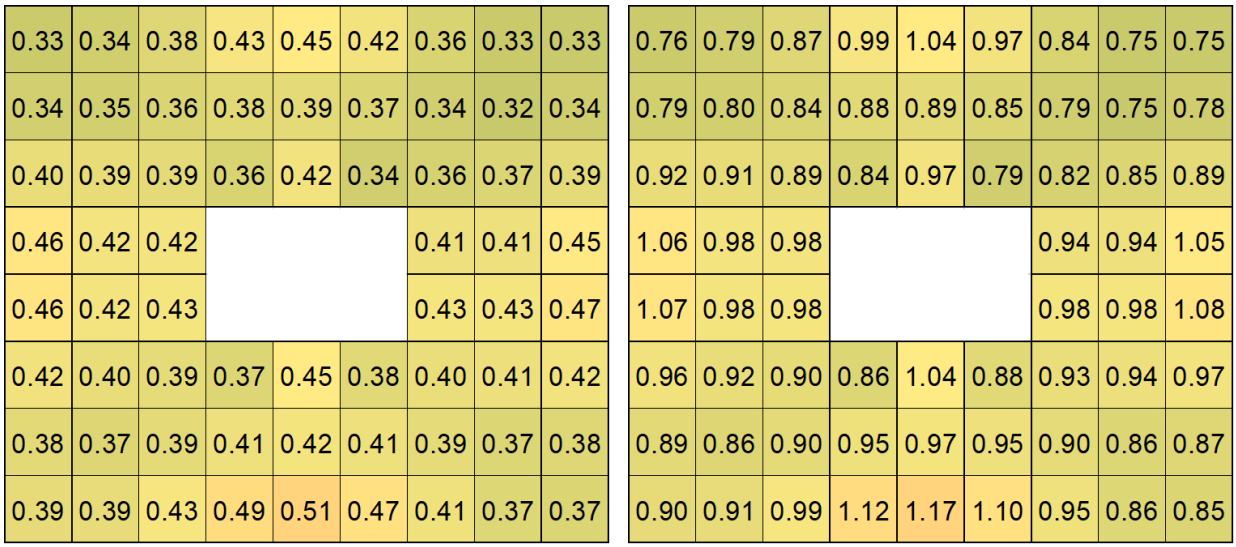
Figure 5. In-plane shear DCRs for LEFE model at displacement equal to the NIFE displacement at peak load (DIMC).



a) NIFE at FC b) LEFE at FC c) LEFE at DIMC



d) Smear averaging (Option A) at FC e) Smear averaging (Option A) at DIMC



f) Averaging along edge elements (Option B) at FC g) Averaging along edge elements (Option B) at DIMC

Figure 6. DCR plot for NIFE and LEFE models for Region A with potential averaging methods.

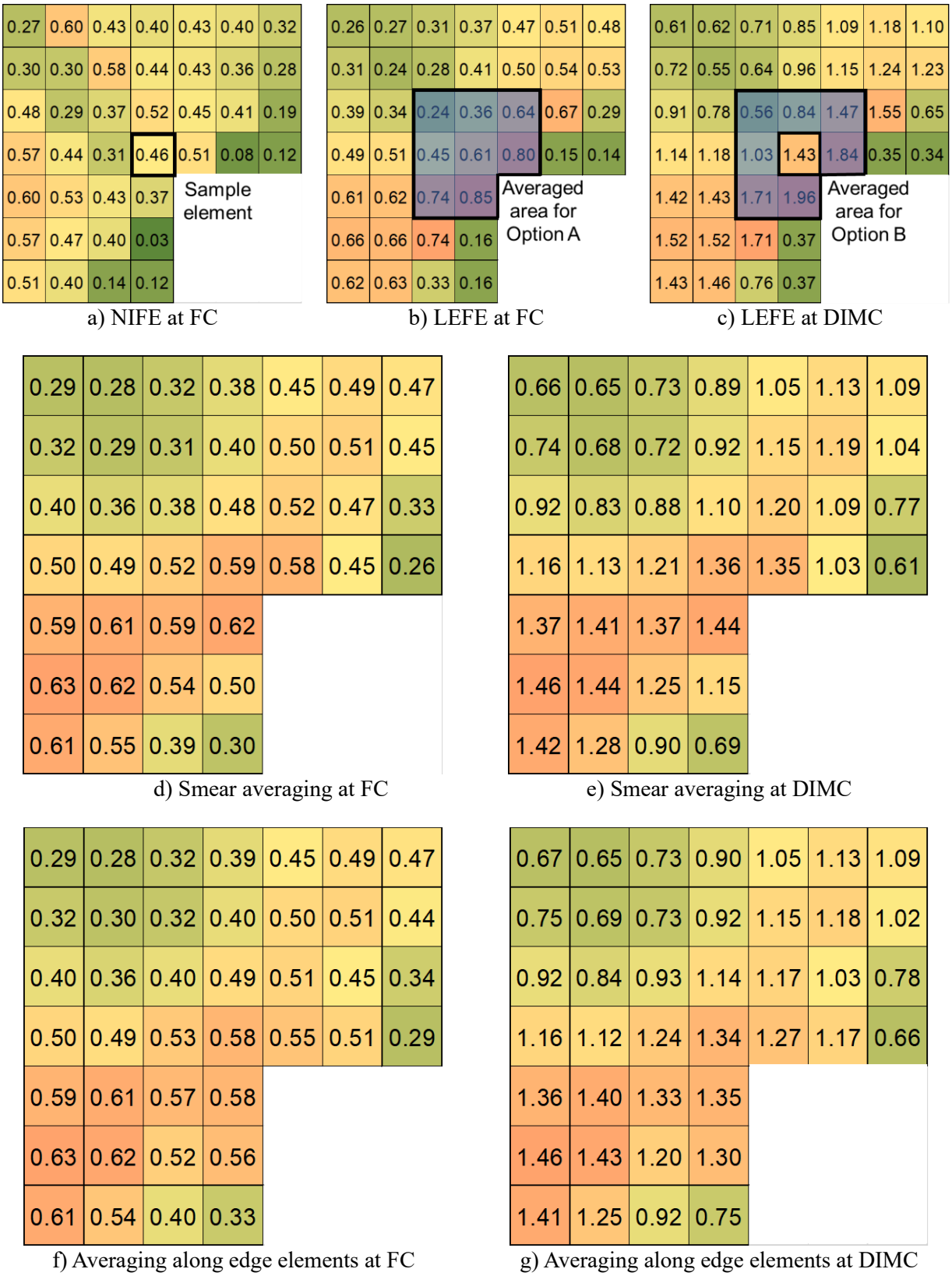
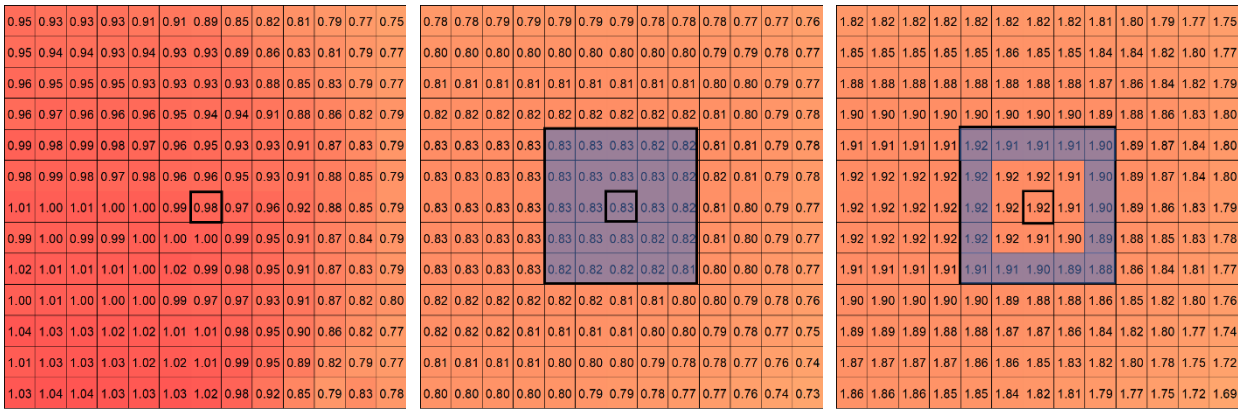
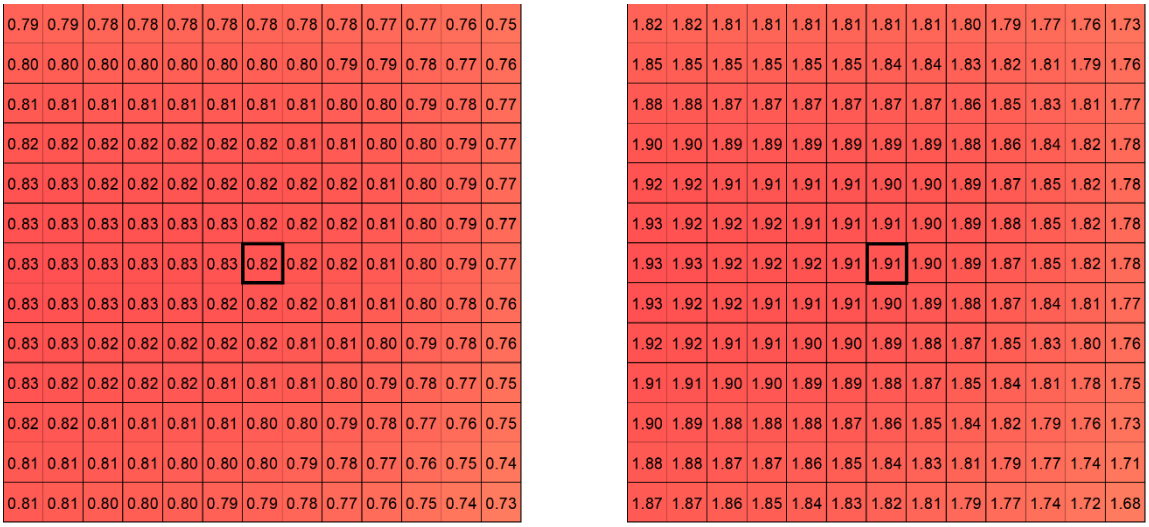


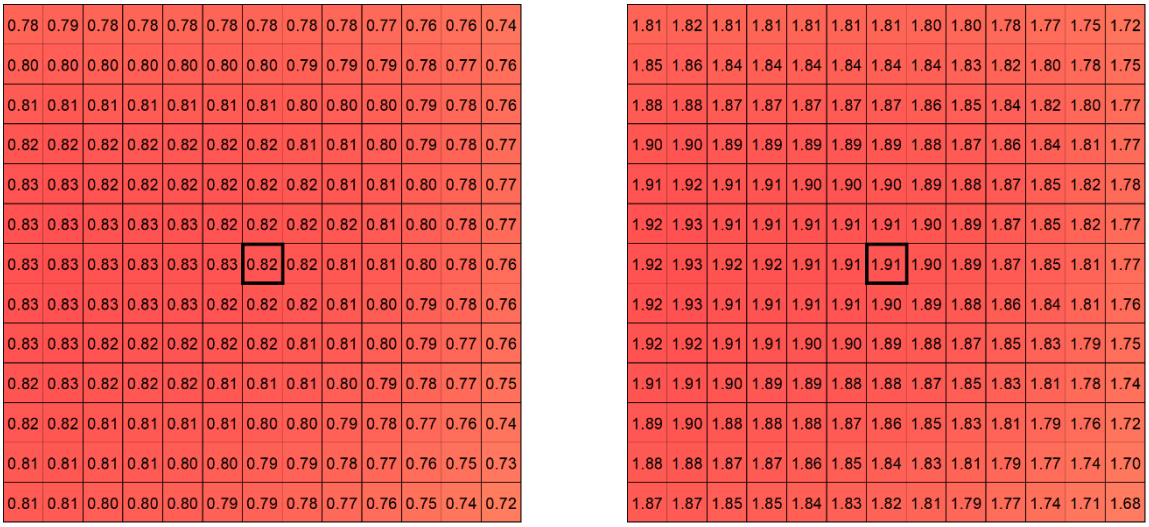
Figure 7. DCR plot for NIFE and LEFE models for Region B with potential averaging methods



a) NIFE at FC b) LEFE at FC c) LEFE at DIMC



d) Smear averaging at FC e) Smear averaging at DIMC



f) Averaging along edge elements at FC g) Averaging along edge elements at DIMC

Figure 8. DCR plot for NIFE and LEFE models for Region C with potential averaging methods

Figure 6 shows the DCR plot for NIFE and LEFE models for Region A (window opening, connection region) with smear averaging (option A) and averaging along the edge (option B) at FC and at DIMC. To illustrate how these options of averaging work, a sample element is highlighted in Figure 6a. For this element, option A of averaging involved using the DCRs of all the elements highlighted inside the box (Figure 6b). Since the sample element does not have any row of elements beneath it in the panel section region, 6 elements are used for averaging (instead of 9 elements that would typically be used). As shown in Figure 6c, option B of averaging involved selecting only the elements around the edge as seen in highlighted portion inside the box. Figure 6d and Figure 6e show the smear averaging (option A) performed over the panel area at FC and DIMC, respectively. Similarly, averaging performed along the edges of the panel area (option B) at FC and at DIMC are shown in Figure 6f and 6g, respectively. It is observed that averaging smoothens out the stress concentration regions in the vicinity of the opening. For this region, options A and B give similar results..

Figure 7 illustrates the effect of two averaging methods by comparing the LEFE and NIFE model DCRs for Region B (corner of door opening, connection region). Averaging was performed over the panel area of $1.5t_{sc}$ x $1.5t_{sc}$. The sample element and the panel region elements for application of averaging method to the sample element are illustrated in Figures 7a, 7b, and 7c. Like region A, averaging options A and B were performed at both FC and DIMC (averaged DCRs are shown in Figures 7d, 7e, 7f, and 7g). While DCR obtained from averaging using both methods at FC were comparable to DCR from NIFE model, DCRs at DIMC were significantly higher than NIFE model. These patterns are similar to those for region A.

Figure 8 presents the effect of two averaging methods by comparing the LEFE and NIFE model DCRs for Region C (interior region). For this region, averaging was performed over the panel area of $2.5t_{sc}$ x $2.5t_{sc}$. A sample element was taken for showing the averaging procedure (Figure 8a). Smear averaging was performed by taking average of demands of all the elements shown inside the highlighted region in Figure 8b. Figure 8c shows the averaging performed along the edge elements where the demands of all the elements lying on the edge of $2.5t_{sc}$ x $2.5t_{sc}$ panel area were averaged. Both averaging methods at FC gave similar results which were comparable to DCR plot of NIFE. But averaging at DIMC yielded higher values which was also observed in other regions considered. Although some of the regions yielded higher DCR values than NIFE model from averaging, the overall contour plot obtained from discussed methods of averaging were comparable to that of NIFE model.

SUMMARY AND CONCLUSIONS

Steel-plate composite (SC) walls in labyrinthine industrial facilities need to be designed for a set of eight internal demands acting simultaneously which include three in-plane forces, two out-of-plane moments, one twisting moment, and two out-of-plane shear forces. To calculate these demands, ANSI/AISC N690 provides the design specifications according to which a linear elastic finite element (LEFE) model should be developed. This approach is computationally inexpensive as compared to a detailed non-linear inelastic finite element model. The LEFE model will show stress concentrations at corners or openings as it cannot account for redistribution of stresses after localized yielding, concrete cracking. Therefore, AISC N690 permits the averaging of LEFE demands over panel section widths of t_{sc} x t_{sc} for connection region and regions around openings, and $2t_{sc}$ x $2t_{sc}$ for interior region, where t_{sc} is the thickness of the wall. However, no procedural guidance is provided for averaging the demands. ACI 349 also does not provide any guidance regarding averaging of these demands and the associated critical sections for averaging.

This paper illustrates the use of two methods of averaging by developing a detailed non-linear inelastic finite element (NIFE) model and an equivalent linear elastic finite element (LEFE) model. Models were developed for a standalone SC shear wall subjected to pushover analysis. In-plane force demand was

extracted for every element from both models. To understand the state at which averaging should be performed, in-plane force demands were extracted from LEFE model at the base shear force equal to the capacity (FC) of the NIFE models, and at the displacement equal to displacement at capacity of the NIFE model (DIMC). Two options: a) smear averaging of demands of all elements occupying panel area, and b) averaging of demands of elements of the panel area along the edges only, were used for the LEFE model. To facilitate the understanding of the averaging techniques, three regions were chosen (one near window, one near door, and one in the interior region) and both techniques were used to get the demands. The reason for choosing these regions was to verify the techniques for both connection region and for interior region. While comparing results from LEFE models at FC and DIMC with the NIFE results, the LEFE DCRs at FC compare well with the NIFE model. However, there are localized stress peaks in the regions around openings and at corners next to the door for the LEFE models. Both the averaging methods reasonably smoothen out these peak stress regions.

The techniques of averaging introduced in this paper need to be used with multiple load combinations, and results from panel experiments to evaluate the effectiveness/correctness of the averaging approaches. Future work includes using the methodology developed in this paper for different loading combinations and labyrinthine SC walls to determine a logical averaging approach for structural walls in safety-related nuclear facilities.

REFERENCES

ABAQUS (2023). *ABAQUS Analysis User's Manual, Version 6.23,* Providence, RI: Dassault Systems Simulia Corp.

ACI 349-13. (2013). *Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary*, American Concrete Institute, Farmington Hills, MI, USA.

ANSI/AISC N690-18. (2018). *Specification for Safety-Related Structures for Nuclear Facilities*

Bhardwaj, S.R., Varma, A.H., Malushte, S.R. (2017). "Minimum Requirements and Section Detailing Provisions for Steel-Plate Composite (SC) Walls in Safety-Related Nuclear Facilities," *Engineering Journal*, New York, USA.

Bhardwaj, S.R., Varma, A.H. (2019). "Design of Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities," American Institute of Steel Construction, Chicago, IL, USA.

Bhardwaj, S.R., Varma, A.H., Orbovic, N. (2019). "Behavior of Steel-Plate Composite Wall Piers under Biaxial Loading," Journal of Structural Engineering, ASCE, Reston, VA, USA.

Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2023). "Effects of Accidental Thermal Loading on In-Plane Shear Behaviour of Steel-Plate Composite Walls," *Engineering Journal*, New York, USA.

CEB-FIP Model Code (1990). "First complete draft", fib bulletins 55 and 56, International Federation for Structural Concrete (fib), ISBN 978-2-88394-095-6 and ISBN 978-2- 88394-096-3

Collins M, Mitchell D, MacGregor J. (1*992).* "Structural design considerations for high strength concrete," *Network of Centers of Excellence on High Performance Concrete*, Toronto, Canada.

Coronado, C., Malushte, S.R., Munshi, J., Verma, N. (2009). "A Rational Seismic Design Approach for Reinforced Concrete Walls for Nuclear Power Plants," *Trans. of SMiRT 20*, Espoo, Finland.

Ollgard, J.G., Slutter, R.G., and Fisher, J.W. (1971). "Shear Strength of Stud Connectors in Lightweight and Normal Concrete." *Engineering Journal*, AISC.

Sierra, C.A.M., Bhardwaj, S.R., Varma, A.H. (2023). "Design of Reinforced Concrete (RC) Wall Panels in Industrial Facilities: Eurocode 'Sandwich' Model Approach," European Journal of Environmental and Civil Engineering*, Taylor & Francis Group,* UK.