Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division V

EFFECTS OF STRUCTURAL RIGIDITY REDUCTION DUE TO CONCRETE CRACKING UNDER SEISMIC LOADS FOR NUCLEAR STRUCTURES

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ABSTRACT

This study develops a methodology to evaluate the effects of reduction in structural rigidity due to cracking in reinforced concrete on the seismic response of structures. It models partially cracked conditions based on the ASCE 4-16 (2017) criteria. The methodology is applied to several power block structures of a nuclear power plant to obtain the Safe-Shutdown Earthquake (SSE) level seismic response. The study compares the seismic response obtained from the partially cracked finite element model with the response using fully cracked and fully un-cracked models. Based on this comparison, the study examines the conservatism or unconservatism associated with these models.

INTRODUCTION

It is generally accepted that cracking in a reinforced concrete structure degrades the structure's stiffness and leads to changes in its frequencies and its dynamic behaviour in response to a seismic event. The seismic response, accounting for the cracking potential could be quantified in a comprehensive non-linear analysis considering the effects on stiffness and damping due to the degree and progression of cracking. However, such an analysis is relatively difficult, resource intensive and needs constitutive relationships that are not readily available. Consequently, the recommendations in ASCE 4-16 (2017) are typically utilized to predict response when cracking is anticipated.

Although the recommendations in ASCE 4-16 (2017) related to cracked stiffness of components, such as a shear wall, apply to average stress conditions, the study presented here instead applies the ASCE 4-16 (2017) cracked stiffness criteria to individual elements in a finite element model of the structure. It thus obtains partially cracked conditions of structural components and then evaluates the structure's seismic response. This seismic response is compared to the seismic response based on the often used fully cracked or fully un-cracked assumptions. The study presents calculated ratios of seismic forces (element force) to illustrate possible conservatism or un-conservatism in the response quantities.

This study examines the response of several structures of a nuclear power plant power block supported on a common base mat. These include the reactor building consisting of a pre-stressed concrete containment and the internal structure, auxiliary buildings, a fuel storage building and electrical service buildings. Most of the structures are seismic Category I. With the exception of the reactor building all other buildings are structurally connected to each other. The analysis reported here uses a coupled model which

includes all of the power block structures as well as the primary coolant loop components consisting of the reactor pressure vessel, a pressurizer, loop piping, reactor coolant pumps and steam generators.

METHODOLOGY

A representative seismic analysis model of a concrete structure generally reflects the best estimate stiffness properties considering the stress state of the concrete members under the seismic loads. The general practice in the nuclear industry incorporates effective stiffness of reinforced concrete elements as shown in Table 1. Damping properties are similarly also adopted based on the response levels. Response level 1 and response level 2 damping values used for un-cracked and cracked finite element models are 0.04 and 0.07, respectively. A finite element model could implement this by assigning to each of the finite elements stiffness and damping properties that are consistent with the state of stress in the element.

Table 1: Effective Stiffness and Damping of Concrete Shell Elements Based on ASCE 4-16 (2017)

MODELS	FLEXURAL RIGIDITY OOP	FLEXURAL RIGIDITY IP	SHEAR RIGIDITY	AXIAL RIGIDITY	DAMPING FOR CONCRETE SHELL
Fully Un-cracked	E_cI_g	E_cI_g	G_cA_w	E_cA_g	0.04
Fully Cracked	$0.5E_cI_g$	$0.5E_cI_g$	$0.5G_cA_w$	$0.5E_cA_g$	0.07
ASCE 4-16 Un-cracked [1]	$0.5E_cI_g$	E_cI_g	G_cA_w	E_cA_g	0.04
ASCE 4-16 Partially Cracked [2]	$0.5E_cI_g$	E_cI_g [3]	$0.5G_cA_w$	E_cA_g	0.07

Notes:
[1] ASCE 4-16 Un-cracked is an intermediate base case model when developing the ASCE 4-16 Partially Cracked model.
[2] The corresponding stiffness values in the "ASCE 4-16 Partially Cracked" are used for only the cracked elements identified based on "ASCE 4-16 Un-cracked" RSA stress results. The damping and stiffness values of concrete shell elements that remained un-cracked do not change. I_g = gross moment of inertia; A_w = web area; A_g = gross area of concrete section; A_s = gross area of reinforcing steel; E_c = modulus of elasticity of concrete; E_s = modulus of steel and G_c = shear modulus of concrete = $0.4E_c$.
[3] Possible reduction of IP flexural rigidity in the "ASCE 4-16 Partially Cracked" model is neglected on the basis of the justifications presented under section "Modelling Un-cracked and Cracked Sections" below.

Analysis Steps

The seismic response of the power block structures to the SSE level ground motion is obtained using the response spectrum analysis (RSA) in ANSYS (2017) combining the modal and directional response quantities in accordance with U.S.NRC Regulatory Guide 1.92 (2007). First, the un-cracked finite element model is developed by replicating the actual material and cross sectional properties of the structural components (*Fully Un-cracked* model in Table 1). Second, the material and cross sectional properties in the un-cracked model are modified to reduce the out-of-plane flexural rigidity of the walls and slabs out-of-plane (OOP) by half in accordance with ASCE 4-16 (see Table 2). This model is referred to here as *ASCE 4-16 Un-cracked* (see Table 1) model. The *ASCE 4-16 Un-cracked* model is used to run the RSA for a particular soil condition.

Based on the results of *ASCE 4-16 Un-cracked* model analysis, the elements exceeding the cracking threshold in shear are identified, and the shear stiffness and damping values for these elements are changed to reflect cracked section properties. The un-cracked properties are retained for the elements that do not exceed the threshold values. Additionally, the stiffness and damping modifications are introduced

only for the shell elements representing the reinforced concrete walls and slabs. The properties of pre-stressed concrete elements, steel members, the reactor coolant system (RCS) line elements, and the base mat (solid elements) remain the same throughout the study. This modified model is referred to here as *ASCE 4-16 Partially Cracked* (see Table 1) model. The RSA is re-run using the *ASCE 4-16 Partially Cracked* model to obtain the corresponding seismic element forces. Based on ASCE 4-16 (2017) these forces are taken to be sufficiently representative of the forces for use in design. The resulting element forces are then compared to the element forces obtained from more conventional *Fully Un-cracked* and/or *Fully Cracked* (see Table 1) model analysis.

The following sections present the threshold stress values used in concrete crack assessment and also discuss how the un-cracked and cracked sections are represented.

Threshold Stress Values

Threshold stress values of concrete provided in ASCE 4-16 (2017) for In-Plane (IP) shear stress and IP flexural stress are $3(f'_c)^{0.5}$ and $7.5(f'_c)^{0.5}$, respectively, where f'_c is compressive strength of concrete in ksi. The threshold limit for Out-of-Plane (OOP) flexural stress is not given as the walls and slabs are always assumed to be cracked in OOP direction.

Modelling Un-cracked and Cracked Sections

The required rigidity values shown in Table 1 are implemented here using equivalent element thickness and equivalent material elastic properties shown in Table 2. In order to maintain the correct component mass an equivalent material density is used along with the equivalent thickness. The resulting stiffness quantities in the IP and OOP directions for the wall and slab elements are summarized in Table 3.

Possible reduction of IP bending rigidity is ignored in the study based on the following justifications:

- The stresses due to IP bending of walls are relatively small because the causative moments (about the horizontal axes) are mostly resisted by connecting walls which effectively act as flanges. The resulting uniform axial stresses on the flange walls are also small due to the large moment of inertia of the overall building cross section.
- Results provided in Table 5 substantiate the above that the membrane stresses exceed the threshold value of $7.5(f'_c)^{0.5}$ for less than 1 percent of all finite elements.

Table 2: Equivalent Properties for Concrete Shell Elements

MODELS	**THICKNESS (t)**	**ELASTICITY MODULUS OF CONCRETE (E_c)**		**SHEAR MODULUS OF CONCRETE (G_c)**		**DENSITY (γ)**
ASCE 4-16 Un-cracked [1][2]	0.707 t	1.4142 E_c		1.4142 G_c		1.4142 γ
ASCE 4-16 Partially Cracked [1][3]	0.707 t	E_{x_c}	1.4142 E_c	G_{xy_c}	0.707 G_c	1.4142 γ
		E_{y_c}	1.4142 E_c			

Notes:
[1] t, Ec, Gc, γ represent the original properties used in the Fully Un-cracked model.
[2] The equivalent properties presented in the second row of the table apply to all shell elements in the ASCE 4-16 Un-cracked model.
[3] The equivalent properties presented in the third row of the table apply only to cracked shell elements in the ASCE 4-16 Partially Cracked model. The equivalent properties in the second row of the table are still applicable to the shell elements that remain un-cracked in the ASCE 4-16 Partially Cracked model.

Table 3: Effective Stiffness Calculation for Concrete Shell Elements

MODELS	MOMENT OF INERTIA IN OOP DIRECTION ($I_{g\ OOP}$)	MOMENT OF INERTIA IN IP DIRECTION ($I_{g\ IP}$)	SHEAR AND GROSS AREAS (A_w - A_g)	FLEXURAL RIGIDITY - OOP	FLEXURAL RIGIDITY - IP	SHEAR RIGIDITY	AXIAL RIGIDITY
ASCE 4-16 Uncracked [1]	$b\,(0.707\,t)^3/12 = 0.35\,bt^3/12 = 0.35I_g$	$0.707t\,b^3/12 = 0.707I_g$	$0.707t\,b = 0.707A_w$ and $0.707A_g$	$1.4142E_c$ $0.35I_g=0.5E_cI_g$	$1.4142E_c$ $0.707I_g=E_cI_g$	$1.4142G_c$ $0.707A_w=G_cA_w$	$1.4142E_c$ $0.707A_g=E_cA_g$
ASCE 4-16 Cracked [1] [2]	$b\,(0.707\,t)^3/12 = 0.35\,bt^3/12 = 0.35I_g$	$0.707t\,b^3/12 = 0.707I_g$	$0.707t\,b = 0.707A_w$ and $0.707A_g$	$1.4142E_c$ $0.35I_g=0.5E_cI_g$	$1.4142E_c$ $0.707I_g=E_cI_g$	$0.5G_cA_w$ [1]	$1.4142E_c$ $0.707A_g=E_cA_g$

Notes:
[1] "b" and "t" are the wall length and thickness, respectively.
[2] Orthotropic materials are used to achieve the corresponding reduction in IP shear rigidity in addition to already reduced flexural rigidity in OOP direction.

ANALYTICAL MODELS AND INPUTS USED IN THE RSA

The base case finite element model of the power block used in the RSA reported here uses the best estimate "Un-cracked" properties and best estimate soil conditions. The soil stiffness is modelled using static soil springs, while the soil damping is considered to be frequency dependent. This model is modified to reduce the OOP bending stiffness for the reinforced concrete floors and walls. The resulting model, called *ASCE 4-16 Un-cracked* model is used for the initial RSA.

The analytical model consists of nine (9) buildings founded on the common foundation mat. The reactor building internal structure and the containment structure are independent and not structurally connected to each other or to the other buildings. All other buildings are structurally connected to each other above the foundation mat. The foundation mat is represented by concrete solid elements, and all other buildings are represented by shell elements. The full finite element model consists of numerous nodes and elements on the order of about 60,000.

The cracking potential for the elements representing the walls and slabs is assessed according to the criteria defined above, and cracked properties are incorporated for these elements as appropriate to develop the *ASCE 4-16 Partially Cracked* model.

Seismic input motion is represented by horizontal and vertical ground motion response spectra (GMRS) characterized by a horizontal PGA of 0.4g. The GMRS resemble standard broad banded shapes used as design basis with peak spectral accelerations (up to 1.0g) in the frequency range of 5 to 10 Hz. The GMRS represent the ground motion input is at the fixed end of the soil springs, and is taken to identical regardless of the elevation of the bottom of the foundation mat. The frequency dependent soil damping is associated with the modal frequencies, and is incorporated in the analysis by using spectral accelerations associated with the modal damping.

RESULTS

Modal Analysis

Table 4 compares the frequencies and participation factors of the dominant modes resulting from the *ASCE 4-16 Partially Cracked* model to the corresponding values from *Fully Un-cracked* and *Fully Cracked* models. The small differences in frequencies and participation factors of individual models in the vertical direction (Z) are attributed to the difference in the OOP flexural stiffness of floors and walls.

The relatively small differences in individual mode frequencies and participation factors in the horizontal directions (X, Y) are attributed to the fact that *Fully Un-cracked* model uses full stiffness for all elements; *Fully Cracked* model uses the reduced IP stiffness for all elements, while the *ASCE 4-16 Partially Cracked* model assigns cracked properties for IP shear only to selected elements.

Table 4: Modal Analysis Results for *Fully Un-cracked, ASCE 4-16 Un-cracked, and Fully Cracked* Models

DIRECTION	FREQ NO	*FULLY UN-CRACKED*		*ASCE 4-16 PARTIALLY CRACKED*		*FULLY CRACKED*	
		FREQ (HZ)	EFFECTIVE MASS RATIO %	FREQ (HZ)	EFFECTIVE MASS RATIO %	FREQ (HZ)	EFFECTIVE MASS RATIO %
X	1	4.96	48	4.25	47	3.76	44
	2	3.46	8	3.44	11	2.44	6
	3	4.76	5	4.04	4	3.83	5
Y	1	4.76	52	4.04	45	3.60	50
	2	3.43	9	3.40	12	2.53	7
	3	4.96	5	4.25	5	3.76	3
Z	1	7.76	25	7.53	53	6.51	32
	2	7.71	24	8.38	6	6.38	12
	3	7.81	20	8.23	4	6.44	7

Cracking Assessment

The element membrane stresses reported by ANSYS (2017) are taken to represent the IP axial and shear stresses in walls and slabs shell elements, and used to compare with the cracking threshold values. These stresses, designated by sm11, sm22, and sm12, for IP axial stress in the local 1-1 axis, IP axial stress in the local 2-2 axis, and IP shear stress, respectively, represent the stresses at the mid-plane of the shell elements and thus exclude flexural stresses due to OOP bending.

Table 5 presents the fraction of the total number of elements in the *ASCE 4-16 Un-cracked* model analysis where the stresses sm11, sm22 and sm12 exceed the respective threshold values for cracking for the power block structures.

Table 5: Crack Element Ratios Obtained from *ASCE 4-16 Un-cracked* Model Analysis

BUILDING NAME	% OF CRACKED ELEMENTS DUE TO SM11	% OF CRACKED ELEMENTS DUE TO SM22	% OF CRACKED ELEMENTS DUE TO SM12
Internal Concrete	0.08	1.89	15.98
Electrical Building	0.16	0.40	29.54
Service Buildings	0.04	0.18	19.75
Storage Building	0.18	1.13	26.27
Auxiliary Buildings	0.20	0.56	30.49
Total	0.15	0.69	25.77

The cracked areas of structural components were mapped to identify vulnerable locations. Based on the review of these maps showing the extent of cracking in the structures the following observations are made:

- The results obtained from the RSA indicate that most of the cracking due to IP seismic shear is associated with shear walls. Very few elements, if any, of the floor diaphragms exceed the threshold stresses for cracking.
- The results also illustrate that, as expected, cracking is more evident at lower elevations as the seismic shear accumulates from upper stories.
- The results for individual walls show that typically not all elements at one elevation are cracked.
- The effect of cracking on the IP bending stiffness can be ignored.
- The cracked elements identified by the *ASCE 4-16 Un-cracked* analysis also exhibit cracked conditions in the *ASCE 4-16 Partially Cracked* analysis. This indeed suggests that further iterations are not expected to significantly improve the seismic response predictions and that the seismic forces resulting from the first iteration of *ASCE 4-16 Partially Cracked* model analysis results in sufficiently representative design basis forces accounting for potential cracking.

Element Force Ratios Based on ASCE 4-16 Partially Cracked and Fully Un-cracked and Fully Cracked Models

Figure 1, for example, presents ratios for seven (7) force quantities resulting from *Fully Cracked* model and the *ASCE 4-16 Partially Cracked* model analyses for all elements of the electrical building. The ± one standard deviation ratios for IP forces are generally in the range from 0.75 to 1.02, while the corresponding ratios for OOP moments vary from 0.85 to 1.41. These ± one standard deviation ranges are similar in the other structures of the nuclear power plant power block.

Conventional analyses often use the *Fully Cracked* and the *Fully Un-cracked* assumptions to obtain bounding design basis seismic forces. Figure 2 and Figure 3 assess this approach by comparing the mean ratios the element forces for the power block structures from *ASCE 4-16 Partially Cracked* runs to *Fully Cracked* and *Fully Un-cracked* assumptions, respectively. The figures also show the mean force ratio of the seven (7) of the structures evaluated (excluding the pre-stressed concrete containment and a secondary structure). These mean values are summarized in the Table 6. The mean ratios for each of the seven (7) stress quantities represent a broad range of structure dynamic characteristics. These results illustrate that for the structures evaluated the conventional analyses underestimate the design basis in-plane shear and overestimates the out-of-plane moments. The *Fully Cracked* model results in a somewhat larger deviation from the “representative” forces than the *Fully Un-cracked* model.

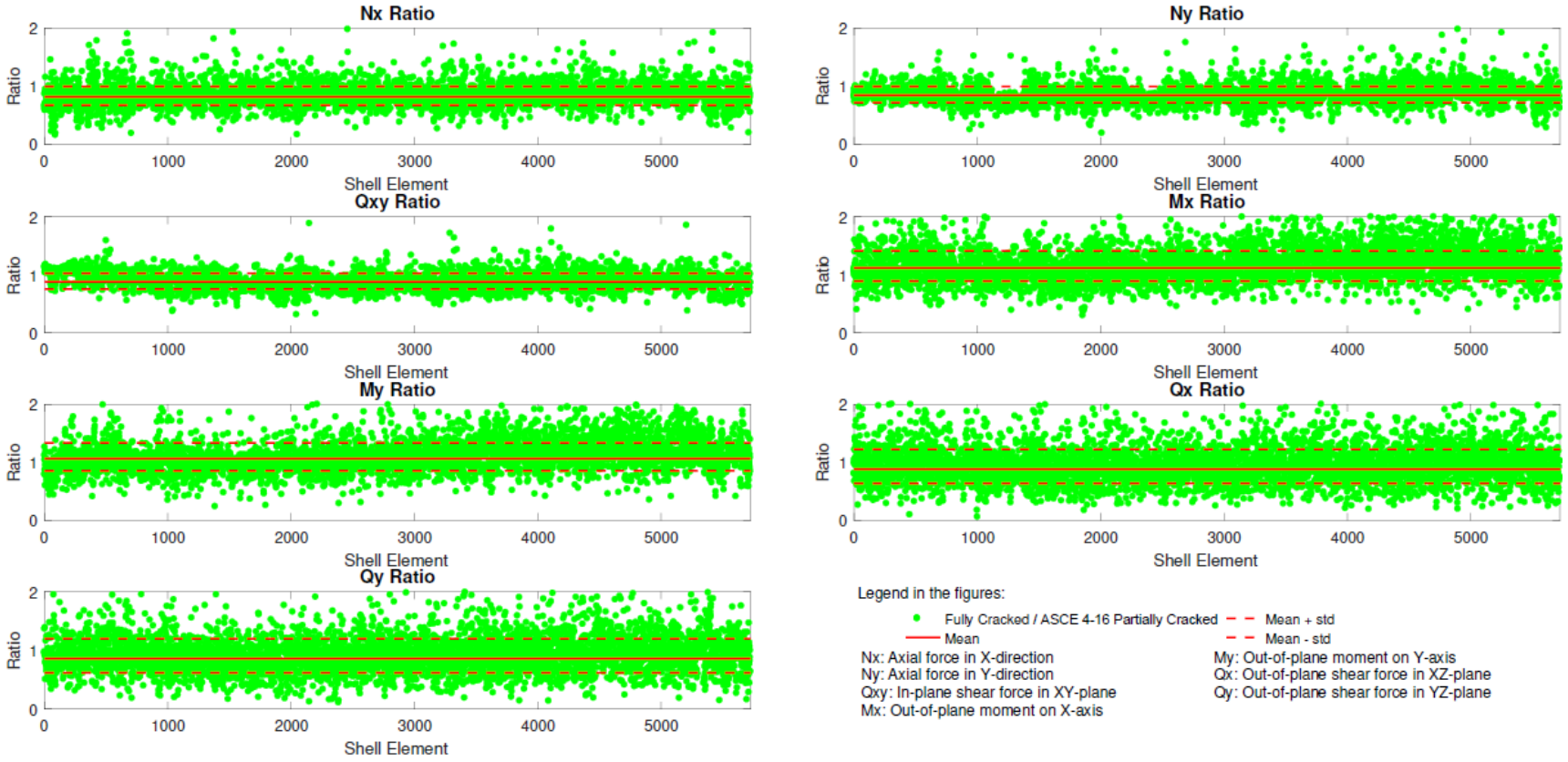


Figure 1: Ratio of Seven (7) Seismic Forces From *Fully Cracked* Model to *ASCE 4-16 Partially Cracked* Model for Electrical Building

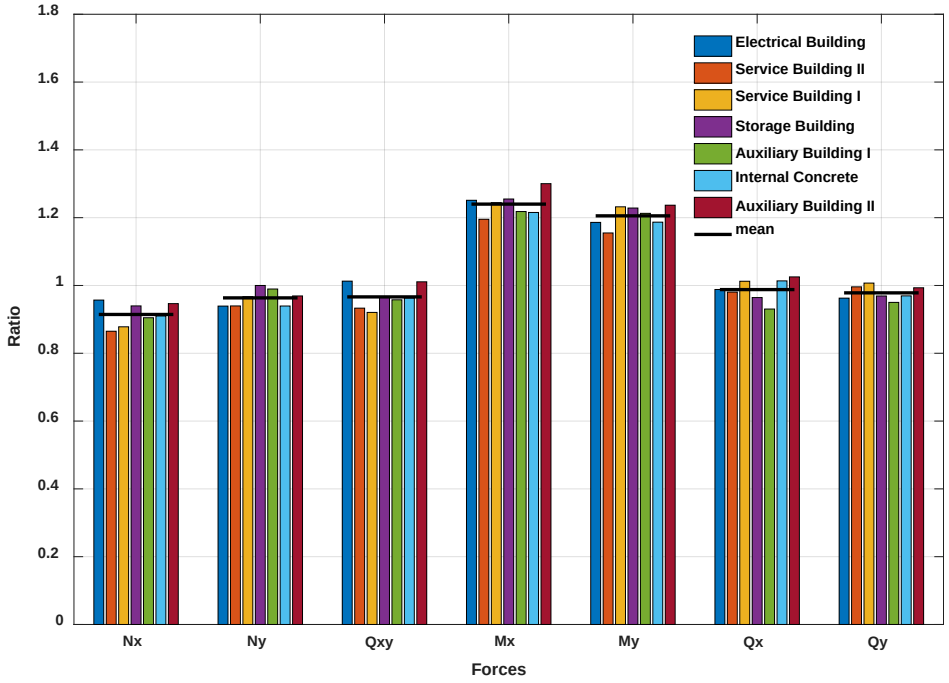


Figure 2: Comparison of Seismic Force Ratios of *Fully Un-cracked* Model to *ASCE 4-16 Partially Cracked* Model

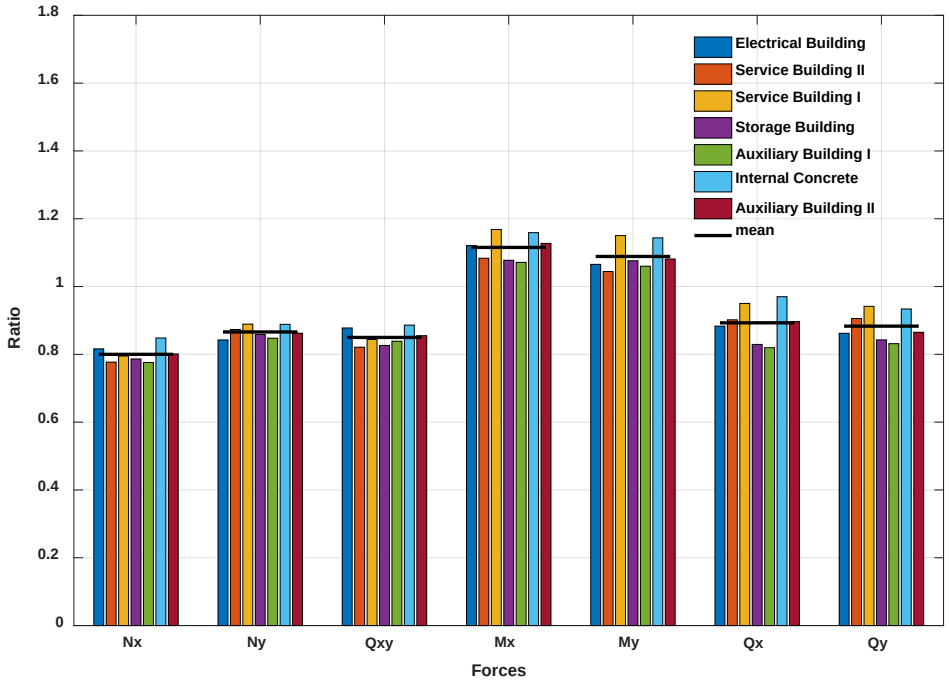
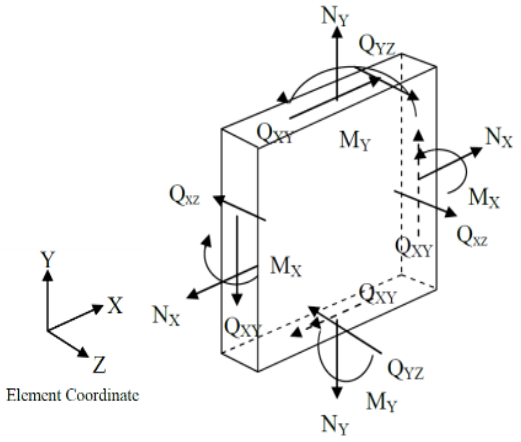


Figure 3: Comparison of Seismic Force Ratios of *Fully Cracked* Model to *ASCE 4-16 Partially Cracked* Model

Table 6: Summary of Seismic Force Ratios for *Fully Cracked* Models to *ASCE 4-16 Partially Cracked* to *Fully Un-cracked*

MODELS	Nx [1]	Ny [2]	Qxy [3]	Mx [4]	My [5]	Qx [6]	Qy [7]
Fully Un-Cracked* / *ASCE 4-16 Partially Cracked	0.91	0.96	0.96	1.24	1.21	0.99	0.98
Fully Cracked* / *ASCE 4-16 Partially Cracked	0.80	0.87	0.85	1.12	1.09	0.89	0.88

Notes:
[1] Nx: Axial force in X-direction
[2] Ny: Axial force in Y-direction
[3] Qxy: In-plane shear force in XY-plane
[4] Mx: Out-of-plane moment on X-axis
[5] My: Out-of-plane moment on Y-axis
[6] Qx: Out-of-plane shear force in XZ-plane
[7] Qy: Out-of-plane shear force in YZ-plane



CONCLUSION

This study evaluates the seismic response of selected power block structures of a nuclear power plant considering the effects on concrete stiffness degradation and damping increase due to cracking. An initial analysis is performed for SSE level ground motions assuming cracking only in the out-of-plane bending (called the *ASCE 4-16 Un-cracked* model). Cracked sections are identified based on the resulting element in-plane stresses relative to cracking thresholds. Then, an additional analysis is performed reducing the stiffness and damping properties of the identified cracked elements in accordance with ASCE 4-16 (2017) recommendations (called the *ASCE 4-16 Partially Cracked model*). The resulting in-plane and out-of-plane forces on walls and slabs from the partially cracked model are then compared to the forces obtained using fully un-cracked and fully cracked assumptions.

The results of the study are judged to be more or less representative of nuclear power plant structures because they are based on the analysis of a broad range of structures and are obtained for ground motion defined by a broad band GMRS which are representative of a wide range of site conditions. The results at the element level do not show a reportable trend for conservatism or un-conservatism of conventional models. The forces predicted by the conventional *Fully Un-cracked* and the *Fully Cracked* model analysis range from about 0.80 to 1.24 times the forces predicted by the *ASCE 4-16 Partially Cracked* model. Based on this study, in-plane forces obtained from the *Fully Cracked* model should be amplified by about 20% on the average. On the other hand, the *Fully Cracked* model is seen to result in somewhat conservative (by 10% to 15%) out-of-plane moments.

Finally, the analytical models developed here represent a methodology to accommodate the effects of partial concrete cracking in predicting seismic forces on structural elements. The study applies the ASCE 4-16 (2017) cracked stiffness criteria to individual finite elements, rather than considering the average wall cross-section shear stress. This modelling approach is judged to be feasible to implement

computationally and is also judged to provide more representative forces for the design of reinforced concrete elements. Although the study only considers the force level response, it can be extended to examine the effects of concrete cracking on the in-structure response spectra for subsequent use in a multistep analysis. Similarly, the extent of cracking in structures can be examined in more detail to develop insights for performing fast nonlinear analysis, which is best suited to structures with a limited number of nonlinear elements

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