Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division VII

OUT-OF-PLANE SHEAR CAPACITY OF REINFORCED CONCRETE WALLS FOR USE IN FRAGILITY AND MARGIN CALCULATION

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ABSTRACT

The out-of-plain (OOP) shear strength for thick reinforced concrete (RC) walls and slabs is often of interest for performance evaluation of earth- or fluid-retaining structures, such as below-grade walls and spent fuel pools in nuclear power plant (NPP) structures. The OOP shear strength of such walls is typically determined based on the criteria for the RC beam shear capacity equations in standards by the American Concrete Institute (ACI) and American Society of Civil Engineers (ASCE). In their recent provisions, both ACI 318 (2019) and ASCE 43 (2019) have updated the OOP shear strength equations to account for dependency of shear strength on the beam depth, which particularly affects deep beams. The update is based on results of studies performed in the past two decades, which are based on extensive test data collected over decades. Their results suggest that deep beams and walls without transverse shear reinforcing may have lower capacities than determined from the older provisions of the ACI and ASCE standards.

The Electric Power and Research Institute (EPRI) recently studied a broader set of test data to confirm the conservatism in the code-based OOP shear strength equations and developed new equations to assess the OOP shear capacity of walls and slabs. The OOP shear strength equations developed by EPRI account for the differences observed between slender and non-slender beams, and each equation takes into account the shear span ratio. The objective of EPRI's study was to develop realistic median capacity and variability for use in fragility and margin analyses of NPP RC wall and slabs for seismic risk assessment. This paper summarizes the main findings and a sample of results of this EPRI research.

INTRODUCTION

The out-of-plain (OOP) shear behaviour of thick reinforced concrete (RC) walls and slabs is often idealized as a wide RC beam with representative boundary conditions. Prior to the publication of the latest edition of ACI-318 in 2019, the shear strength of RC beams has been commonly computed using $2\lambda\sqrt{(f'_c)}b_w d$, which is the nominal simple shear capacity equation in ACI 318-14 and prior editions. In this equation, λ is the modification factor to reflect the reduced mechanical properties of lightweight concrete, f'_c is the specified compressive strength of concrete (psi), b_w is the web width (in.), and d is the effective section depth (in.).

ACI 318-14 and prior editions assumed that the concrete shear capacity of an RC beam does not depend on its effective depth. However, many research studies (e.g., Bazant et al. (2007); Sneed and Ramirez (2010); Reineck et al. (2010)) have argued strong dependency of the RC beam shear strength on the effective depth. Neglecting such dependency in the code equation could result in an unconservative estimation of shear strength, particularly for deep RC beams. Research has shown that deep beams and walls without transverse shear reinforcing have lower capacities than those determined from the traditional provisions of the design standards, such as ACI 318-14. As a result of such studies and based on expansive test data collected over decades (Reineck et al. 2013 and 2014), new provisions of standards by ACI and ASCE (ACI 318-19 and ASCE 43-19) established updated equations for concrete shear capacity to account for the dependency of shear capacity on effective depth. These updates include introducing factors that capture the size effect on the shear strength, and, in general, reduce the beam shear strength as the depth increases. Parsi et al. (2022) reviews the technical basis for the correction factor included in ASCE 43-19 and ACI 318-19 equations and assesses their performance using the available test data.

The shear behavior and failure mechanism of the RC beams without transverse reinforcement is complex and dependent on several aspects of the beams. A beam property that significantly affects the shear strength and failure mechanism of RC beams is the shear span-to-depth ratio. While the updated code provisions for shear strength capture the effect of beam depth, they do not account for the dependency of strength on the shear span-to-depth ratio. Analysis of test data indicates that capacities for beams with shorter shear span-to-depth ratio tend to be under-estimated when using design code equations. Thus, the shear strength equations are conservatively biased for the beams with a relatively small shear span-to-depth ratio, such as a beam that characterizes a nuclear plant shear wall. This conservatism in the code is typically tolerated in design. However, this underprediction of strength can be significant in the evaluation of existing structures and seismic probabilistic risk assessments (SPRAs) of the nuclear power plants (NPPs), where the objective is to develop realistic strengths to provide the best estimates of the risk.

The Electric Power and Research Institute (EPRI) recently studied a broad set of test data to confirm the conservatism in the code-based shear strength equations for beams with relatively small shear span-to-depth ratio and developed new equations for evaluation of walls and slabs OOP shear capacity. The EPRI research was introduced in Hardy et al. (2019) and shown to be necessary for developing realistic characterization of the shear capacity of members without transverse reinforcing for use in seismic margin and seismic fragility calculations. EPRI's research was completed in 2020 and documented in EPRI 3002018218 (2020). This paper summarizes the main findings and sample of results of this EPRI research.

FAILURE MECHANISM OF RC BEAMS IN SHEAR

The shear failure mechanism of the RC beams without transverse reinforcement is complex and dependent on several aspects of the beams, including the shear span-to-depth ratio. For a simply-supported beam with point loading, the shear span-to-depth ratio, a/d, is defined as the shear span a, the distance from the support to the point of load application, and the effective depth d, the distance from extreme compression fiber to the centroid of the longitudinal tension reinforcement (Figure 1a).

Generally, beams with shorter a/d are considered "short beams" while those with higher a/d are considered "slender beams". There is no definitive a/d threshold where the transition from slender to short occurs. However, multiple researchers (e.g., Joint ASCE-ACI Task Committee 426) have identified ratios in the range of 2 to 3 for the transition. For example, Wight (2012) divides the a/d into four regions: very short ($a/d \leqslant 1$), short ($1 < a/d \leqslant 2.5$), slender ($2.5 < a/d < 6.5$), and very slender ($a/d \geqslant 6.5$). The controlling capacity of an RC beam is governed by different failure modes (Figure 1b), which are dependent on a/d:

- Very short beams carry the load through arching action, with the longitudinal steel acting as a tension tie between supports.
- Short beams under shear load develop inclined cracking. However, after internal load redistribution, a secondary arch-type mechanism occurs, and the load is resisted in flexure by a force couple between the concrete in compression and the longitudinal reinforcement in tension. The failure mode of this arch-type mechanism is either failure of the concrete in the compression zone (known as shear-compression failure) or failure of the anchorage or bond of the longitudinal reinforcement (known as shear-tension failure).

- Slender beams tend to fail due to inclined cracking. The shear strength for slender beams is approximately the load at which inclined cracks form and pass through the neutral axis (that is, crack extends into the beam compression zone).
- Very slender beams fail in flexure before the development of inclined shear cracking.

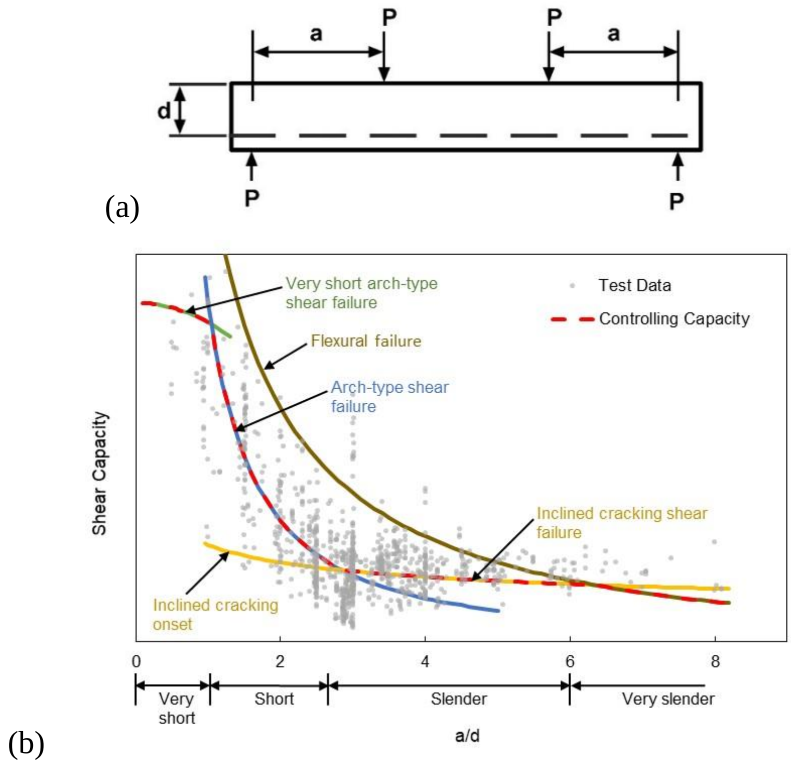


Figure 1. (a) shear span parameter, (b) relationship between modes of failure for simply-supported beams

The failure type is not solely determined from the *a/d* of the member. Other parameters such as the longitudinal reinforcement ratio ρ_w, the member depth d, and the concrete compressive strength f'_c also play a role in the maximum shear strength and the failure mode that occurs. The effect of these different parameters should also be considered when developing realistic predictive equations for the shear strength of concrete beams without transverse reinforcement.

Using available test data, Hardy et al. (2019) studied the ratio of the tested shear capacity, V_{test}, over the historic ACI nominal shear capacity calculated by $Vn_{ACI} = 2\lambda\sqrt{(f'c)}b_w d$, against several parameters of interest such as *d*, ρ, and *a/d*. Several important conclusions from the review of the test data were:

- The shear strength of slender beams has a strong dependency on *d* and ρ_w. The historic shear capacity equation overpredicts the shear strength for deeper slender members and those members with low longitudinal reinforcement ratios, while it underpredicts shear strength for shallow members, and those with larger reinforcement ratios, the shear strength.
- The shear capacity of short members is not heavily influenced by *d* and ρ_w. as there is no strong correlation between shear capacity and these parameters.
- The shear strength of short beams has a strong dependency on *a/d*. The shorter the shear span, the higher the shear capacity. With shorter *a/d*, the secondary, arch-type failure mechanism can form and result in a higher shear capacity.
- The shear strength of slender beams does not show as strong a dependence on *a/d*. For the slender beams, an alternate load path related to the shear span (arch-type mechanism) cannot form, so an increase in shear resistance is not possible.

These key conclusions are important to understand the shear behaviour of RC beams, particularly for short beams that can resemble thick and short-spanned concrete walls and slabs.

POTENTIAL CONSERVATISM IN SHEAR STRENGTH EQUATIONS

The shear strength equations in ACI 318-19 and ASCE 43-19 introduce correction factors as functions of the beam depth and reinforcement ratio. These updated equations do not account for the dependency of shear strength on *a/d*. The dataset used in the development of those equations only included the slender beam database. As demonstrated in Figure 2-c, the slender beam shear strength is not sensitive to *a/d*. Most designs in commercial applications are for RC sections in the slender range, and consideration of *a/d* effects on shear strength is not significant for such applications. However, for calculation of OOP shear capacity of thick and short-spanned walls, such as typical RC walls of spent fuel pool (SFP) structures in the nuclear power plants, neglecting *a/d* effects can be very conservative.

Table 1 lists the correction factors in ASCE 43-19 and ACI 318-19 in shear strength equations for eight example SFP walls using the wall information provided in EPRI 3002009564 (2017). Table 1 shows that the correction factor can be as low as 0.23. This is a significant, and overly conservative, reduction from the original design capacity developed using the historic concrete shear capacity equation $2\lambda\sqrt{(f'_c)}b_wd$. Figure 2 shows the ratio of the tested shear capacity V_{test} over the $2\lambda\sqrt{(f'_c)}b_wd$ (i.e., the ACI nominal shear capacity per Eq. 22.5.5.1 of ACI 318-14). As shown in these plots, the test data from beams with *a/d* less than 2.4 does not suggest a need for any reduction in shear strength due to the increased depth. Therefore, using ASCE 43-19 and ACI 318-19 shear strength equations for beams with *a/d* less than 2.4 results in an unnecessary conservatism.

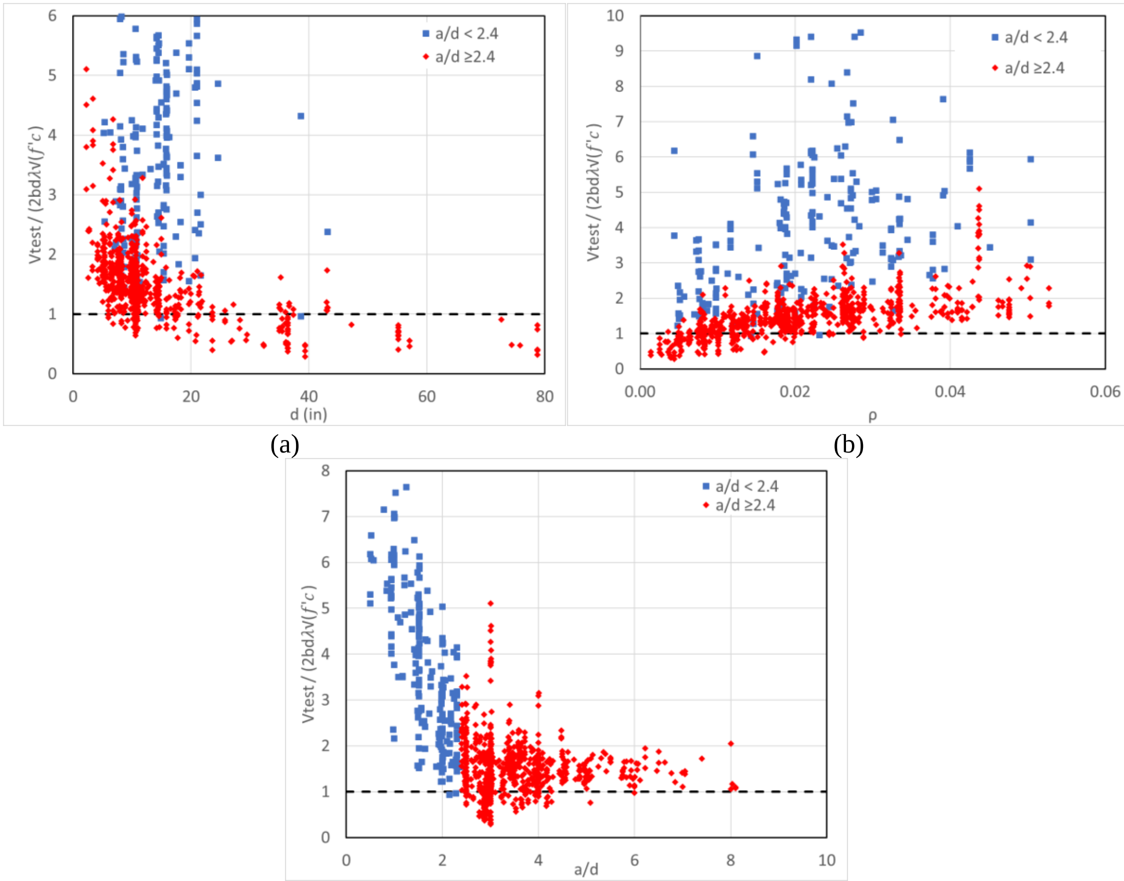
Table 1: Comparison of Code Correction Factors

Wall Thickness, *t*	**Effective Depth, *d* [1]**	**ρ_w [2]**	**ASCE 43-19 Size Correction Factor**	**ACI 318-19 Shear Strength Reduction Factor**
72 in.	68 in.	0.30%	0.25	0.29
72 in.	68 in.	0.20%	0.23	0.26
66 in.	62 in.	0.30%	0.26	0.30
60 in.	56 in.	0.80%	0.35	0.44
60 in.	56 in.	0.20%	0.25	0.28
72 in.	68 in.	0.30%	0.25	0.29
72 in.	68 in.	0.30%	0.25	0.29
57 in.	53 in.	0.20%	0.26	0.28

1. The effective depth *d* is estimated as the wall thickness t minus 4 in.
2. The reinforcement ratio ρ_w is calculated based on the total tensile reinforcement area (does not include all curtains of reinforcement).

STRENGTH EQUATION DEVELOPMENT APPROACH

A median-centered predictive shear strength equation is developed by using test data considering the effects of a wide range of variables. This study uses a wider range of test data compared to that used in ACI and ASCE, including beams with *a/d* as low as 1.0.



(a) (b)

(c)

Figure 2. Test to code ratio versus (a) effective beam depth *d*, (b) reinforcement ratio ρ_w (c) shear span-to-depth ratio, *a/d*

This study uses a dual failure mode approach, which is, in principle, similar to the study performed by Kennedy (1967). However, it uses a larger set of test data available in the ACI database (Reineck et al. 2013 and 2014) and develops relatively simpler and more practical equations than those developed by Kennedy (1967).

Data regression is used to develop two equations based on the Kennedy approach: one for the inclined cracking failure shear capacity, and one for the arch-type failure capacity. The data regression to calculate the shear capacity equations incorporates the same factors ρ_w and d as the proposed ASCE correction factor, but also considers the *a/d* and concrete compression capacity f'_c directly. The approach does not rely on a hard division for *a/d* to identify an applicable equation to calculate the shear capacity. The transition zone between inclined cracking and the formation of the arch-type mechanism cannot be characterized by a single value of shear span. However, the general behavior is that as *a/d* decreases, there is a point at which the higher capacity arch-type failure mechanism can form. Based on this behavior, for a given beam cross-section, both shear capacities are calculated, and the larger of the two capacities is the controlling shear capacity. The two developed equations can capture two different potential failure modes and do not act as a modifier to the current code capacity.

DATA PROCESSING

Data Filtering

The data used in this study is from the ACI database of tested beams without transverse reinforcement. The basic strength equations are developed for simply supported beams with rectangular cross-sections and concentrated point loads. Therefore, the beam test data is filtered to only include simply supported rectangular beams with point loading. The test data from other beam conditions, such as beams with distributed loads, are also used in regression analyses for refinement of the preliminary shear strength equations to capture the effects of different loading and boundary conditions.

The test data is also filtered to exclude beams with extreme configurations and only include beams with reasonable ranges of properties. These ranges are determined based on engineering judgment, sensitivity studies, and a review of approximately 40 typical concrete wall configurations at ten different NPPs. The lower bound (LB) and upper bound (UB) values of each parameter before and after filtering are shown in Table 2. The total number of rectangular beams with point loads is 902 out of the 1006 beams total.

Binning and Re-binning Data Based on Governing Equation

The database is first de-aggregated to develop strength equations for the inclined cracking and arch-type failure modes. Because the data base does not include information on the failure type, *a/d* is initially assumed to be the factor that differentiates between different failure modes: beams that are presumed to be slender and fail in inclined-cracking and (2) beams that are presumed to be short and fail in an arch-type mechanism. However, as discussed earlier, there is no finite transition of *a/d* at which one failure mode dominates the other, and other beam properties can influence the beam failure mode. An initial *a/d* of 3.0 is used to separate the database into groups of slender beam, and short beam data and regression is performed accordingly on the two datasets for slender and short beams to develop two preliminary strength equations for the two failure modes.

Table 2: Tested Beam Parameter Limits

Parameter	**Before filtering**		**After filtering**	
	Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
a/d	0.3	8.1	1	7.1
f'_c	1,500 psi	20,000 psi	1,600 psi	7,700 psi
L	16 in.	770 in.	24 in.	685 in.
d	2.6 in.	79 in.	5 in.	79 in.
b_w	2 in.	118 in.	4 in.	118 in.
ρ_w (1)	0.001	0.066	0.004	0.041
f_y	39 ksi	258 ksi	39 ksi	80 ksi

(1), In addition to UB limit applied to ρ_w, samples with tensile strain lower than 0.002 are also filtered to ensure sample beams used in regression analysis are not overly reinforced and are not compression-controlled.

Concrete beams that fail in shear, regardless of being slender or short, will initially develop an inclined shear crack. For slender beams, this inclined crack leads to failure of the beam. However, as *a/d* decreases toward short beams, there is a point at which the higher capacity arch-type failure mechanism can develop after the initiation of the inclined crack. Based on this behavior, for a given beam cross-section, the controlling shear capacity is the larger of the capacities developed based on two failure modes: inclined cracking and arch-type failure mechanism. This understanding is used to better characterize the beam failure mode: after the initial data regression using the data aggregated by *a/d* of 3.0 the shear strength of each sample is computed using both preliminary equations. For each beam in database, the beam failure mode is then determined based on the strength equation that results in a higher shear capacity, and the sample is re-binned into short or slender accordingly. Two regression analyses are then repeated using the tested beam data re-binned into groups of slender and short beams.

For illustration purposes, the shear capacity of a beam section with varying *a/d* using equations for short and slender beams are overlaid on the test data (Figure 3). Both the individual trends of the slender and short equations are shown as well as the controlling envelope. The plots of the results of slender and short equations demonstrate the transition from inclined cracking failure to arch-type failure and reasonably capture the trends of the slender and short beam data.

REGRESSION ANALYSIS

Two strength equations are developed for the two failure modes by linear regression analyses using datasets for slender and short beams. The dependent variable (*A*) is a function of shear strength, and the independent variables are properties of the beam significant to the shear strength, including shear span-to-depth ratio, *a/d*. The following normalized equation form is defined for data regression:

$$LN(A) = K_0 + K_1 LN(B_1) + K_2 LN(B_2) + K_3 LN(B_3) + K_4 LN(B_4) \qquad (1)$$

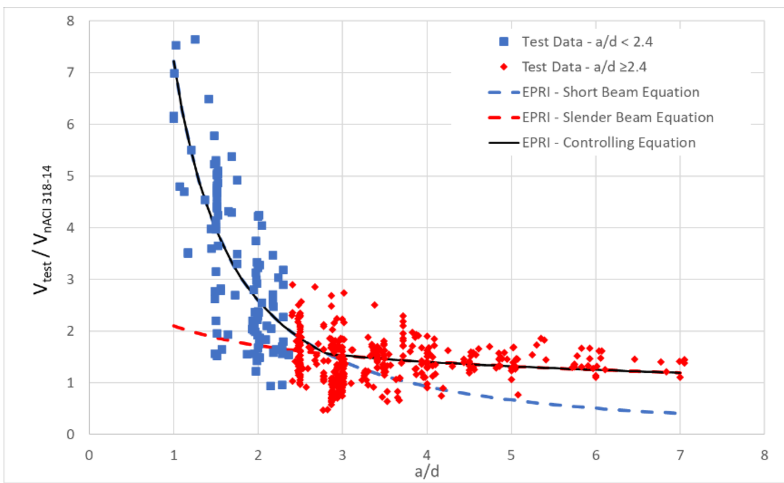


Figure 3. Equation trends and enveloping capacity overlaid on beam test data

LN(*A*) is a function of the beam ultimate shear strength (V_{ult}), for inclined cracking failure mode and a function of beam moment at ultimate shear strength (Mv_{ult}) at the location of applied load, for arch-type failure mode. The independent variables B_1 through B_4 are respectively functions of *a/d*, effective depth (*d*), specified compressive strength of concrete (f'_c), and the ratio of tension reinforcement area to concrete effective cross-sectional area (ρ_w). Coefficients K_0 to K_4 are obtained by linear regression analysis using the least-squares approach. The dependent and independent variables are defined as dimensionally compatible to minimize the correlation between the variables that are judged to be independent, which is desirable in regression analysis.

MODIFICATION FOR DIFFERENT CONFIGURATIONS

The ACI database (Reineck et al. 2013 and 2014) includes 37 simply supported beams that were tested under uniformly distributed loads. The database does not include any test data for beams with continuity over the supports. Moody et al. (1955), however, reports test results for 78 samples of beams without transverse reinforcement, with point loads, and with continuity over the supports. The small database available for beams with distributed loads or continuity over the support does not allow for the development of separate set of prediction equations for such beam configurations. Therefore, the best estimate shear strength equations developed for beams with point load are adopted and modified to predict the shear strength of uniform distributed loads and continuous over supports . The modifications include:

- Adjusting *a/d* based on the equivalent shear span for different configuration.
- Applying modification factors determined based on regression analysis of the limited available data.

EPRI 3002018218 provides details and additional criteria for beams with uniform loading and for continuous beams over supports.

EXAMPLE APPLICATION

The OOP shear strength of fluid-retaining walls, such as SFP walls, is typically one of the potentially governing failure modes of the SFPs in SPRAs. That is because the SFP walls are under substantial uniform fluid pressure in the OOP direction. The OOP shear strength of these walls is determined by idealizing the wall as a wide RC beam with appropriate boundary conditions.

The shear strength is computed for eight examples of SFP walls with different properties and configurations using the shear strength equations given in ACI 318-14, ASCE 43-19, ACI 318-19, and the equations developed in this EPRI study. The shear strength computed based on ACI and ASCE equations does not include strength reduction factors comparable to the EPRI's median strength equations. Figure 5 shows the comparison of the computed strength using different equations.

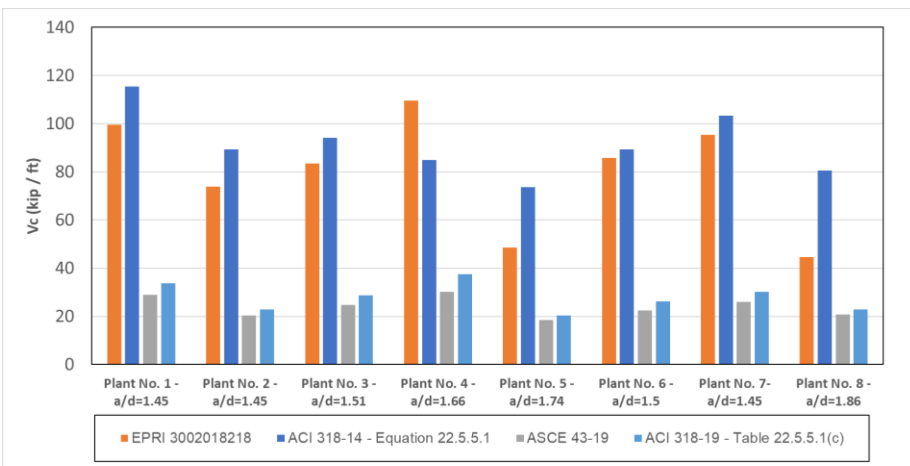


Figure 5. Shear strength of example spent fuel pool walls based on different equations

The comparison chart shows that the updated ACI 318-19 and ASCE 43-19 shear strength equations result in substantially lower shear strengths as compared to the ACI 318-14 nominal shear capacity ($2\lambda\sqrt{f_c'}b_w d$). When using the updated ACI and ASCE equations, the shear strength of the walls is drastically reduced because of the penalizing factors in those equations for the relatively large thickness of the walls. These equations do not account for the relatively short shear span (i.e., small *a/d*) of these typical SFP walls. EPRI's equation, however, accounts for both high thickness and small *a/d* of these walls and results in less conservative estimates of shear strength. Figure 5 shows the excessive conservatism resulting from using recent provisions of the ACI 318 and ASCE 43 for estimation of OOP shear strength of these example SFP walls. Such excessive reduction in shear strength is likely consequential in an SPRA study as it can cause the SFP failure to be a low-capacity component governing the seismic risk. Using

EPRI's equation accounts for all properties affecting wall shear strength and, for these example walls, results in shear strength comparable to the ACI nominal shear capacity given by Eq. 22.5.5.1 of ACI 318-14 ($2\lambda\sqrt{f_c'}b_w d$), while also conforming better to the available data (Figure 3).

APPLICABILITY AND LIMITS OF SHEAR STRENGTH EQUATIONS

There are some limitations in the application of the shear strength prediction equations discussed in this study. The equations developed in this study are based on a specific set of data with reasonable ranges for different beam properties. Application of the equations to determine shear capacities of elements with parameters outside the ranges considered in this study requires evaluation and justification by the user. Moreover, to prevent possible over-estimation of shear strength using equations developed in this study, maximum shear strength is defined to be $12\sqrt{f_c'}b_w d$. This maximum shear capacity is intended to capture both the limits of the data and the transition to a different failure mode at low *a/d* values.

Lastly, applying the shear strength equation based on the arch-type failure mechanism relies on the sufficient development length of the longitudinal reinforcing. Therefore, using strength equations in this study is limited to sections where the longitudinal reinforcing is fully developed on either side of the critical section at a distance *d* away from the face of the support. If the longitudinal reinforcement is not sufficiently developed, the shear strength is limited to that determined by the inclined cracking failure mode.

SUMMARY AND CONCLUSION

This paper summarizes the major results of the research study documented in EPRI 3002018328 (2020), which assessed the effects of shear span-to-depth ratio on shear strength of beams. The study develops median-centered shear strength equations for calculations of realistic median capacity for concrete members without transverse reinforcing for use in fragility analyses in SPRAs. The developed equations were based on test data for simply supported beams without transverse reinforcement and with point loads. Equations are developed for two shear failure modes: arch-type and inclined cracking. Correction factors are developed to account for different loading and boundary conditions: simply supported with distributed loads, and continuous beams with point loads.

Example applications of the developed shear strength on eight example concrete walls for SFP are presented. The comparison of the computed strength using different equations shows that the updated ACI 318 and ASCE 43 shear strength equations result in substantially lower shear strengths as compared to the historic ACI nominal shear capacity ($2\lambda\sqrt{f_c'}b_w d$). The updated ACI and ASCE equations reduce the shear strengths because of the penalizing factors in these equations for the relatively large wall thicknesses. EPRI's equations discussed in this paper account for both high thickness and small *a/d* of the walls and result in less conservative and more realistic estimates of shear strength. Such realistic shear strength equations are essential in SPRA studies because they prevent false determination of the structures with thick walls (e.g., SFP structures) as the low-capacity components that govern the seismic risk.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the late Dr. Robert Kennedy and Dr. Andrew Whittaker for their support and guidance in the development of this research.

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