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

REINFORCED CONCRETE SHEAR WALL CAPACITY ADVANCES

Greg S. Hardy[1], Tim Graf[2], Riccardo Cappa[3], John Richards[4]

[1]Senior Principal, Simpson Gumpertz & Heger, Newport Beach, CA, USA (GSHardy@sgh.com)
[2]Project Manager, Simpson Gumpertz & Heger, Newport Beach, CA, USA (TJGraf@sgh.com)
[3]Staff II, Simpson Gumpertz & Heger, Newport Beach, CA, USA (RCappa@sgh.com)
[4]Technical Executive, Electrical Power Research Institute, Charlotte, NC, USA (JRichards@epri.com)

The authors wish to recognize Robert P. Kennedy for his key contributions to this research

ABSTRACT

Seismic PRAs have become more common in the nuclear power industry following the Fukushima accident caused by the 2011 earthquake and tsunami. In order to provide best estimates of the risk, the seismic fragilities should be as realistic as possible. Nuclear plant reinforced concrete (RC) structures have traditionally exhibited high seismic capacities within seismic probabilistic risk assessments (SPRAs). For the existing fleet of nuclear power plants (NPPs), RC walls and slabs were commonly constructed without out-of-plane (OOP) or transverse shear reinforcement. The capacity for these RC elements has typically been empirically derived based on code equations for the concrete shear strength of RC beams. Research of a broader set of beam shear test data is now showing that beams with little or no transverse reinforcing may not have the shear capacities predicted by current American Concrete Institute (ACI) codes. The Electric Power and Research Institute (EPRI) has begun a study to research the basis of these proposed reductions, and if appropriate, develop new equations to assess the OOP shear capacity of walls and slabs. The goal is to assess what a realistic median capacity and variability would be for use in fragility analyses and to consider how that updated fragility could affect SPRAs.

INTRODUCTION

The OOP behavior of walls and slabs can be idealized as a wide simply-supported beam spanning from wall or slab support points. Using this idealization, the results of the beam shear tests are extrapolated to wall and slab OOP capacities for RC members without transverse reinforcing. By developing an approach to calculate the shear strength of beams without transverse reinforcing, a refinement of the calculation of the OOP shear capacity of walls or slabs can also be achieved.

The results of the beam shear test data have been used to develop new shear strength approaches that are being recommended for inclusion to two key structural codes: ACI 318 and American Society of Civil Engineers (ASCE) 43. These codes form the basis for both the current designs of many nuclear structures, but also the basis for the seismic margin and seismic fragility calculations being conducted. The reductions in strength being proposed are significant to the OOP shear strength of walls and slabs. These reductions become significant for the performance of walls with significant OOP demand and earth- or fluid-retaining structures. Using these reductions in the evaluation of existing RC nuclear structures could result in a challenge both to the seismic design basis and to beyond design basis assessments if they are enacted into the codes and standards.

SHEAR FAILURES OF BEAMS WITHOUT TRANSVERSE REINFORCING

The shear behavior of a RC beam without transverse reinforcing is complex and is dependent on several aspects of the beam properties. The most predominant characteristic for determining the failure mode is the shear span ratio, a/d. Where, as shown in Figure 1, *a* is the shear span, the dimension from the support to the point of load application, and *d* is the distance from extreme compression fiber to centroid of longitudinal tension reinforcement. The shear span roughly defines whether the beam is slender, or non-slender. There is no clean distinction where the transition from slender to non-slender occurs, but the Joint ASCE-ACI Task Committee 426 (1973) classifies non-slender beams as beams having an a/d ratio between 1 and 2.5, and slender beams having an a/d ratio greater than 2.5.

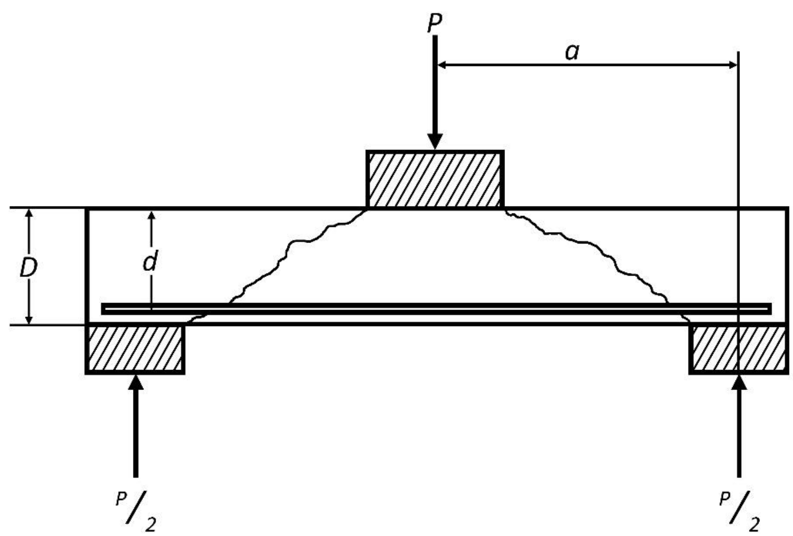

Figure 1: Important Shear Span Parameters

Using this slender/non-slender transition, the Joint ASCE-ACI Task Committee 426 (1973) summarized the different shear failure modes for each beam type. For slender beams, the failure mode is diagonal tension failure, shown schematically in Figure 2. For non-slender beams, the failure mode is shear-compression failure, shown schematically in Figure 3.

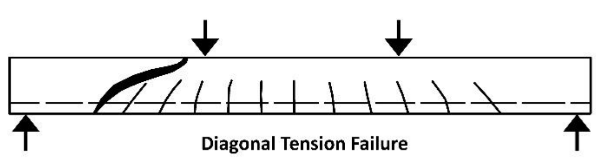

Figure 2: Diagonal Tension Failure

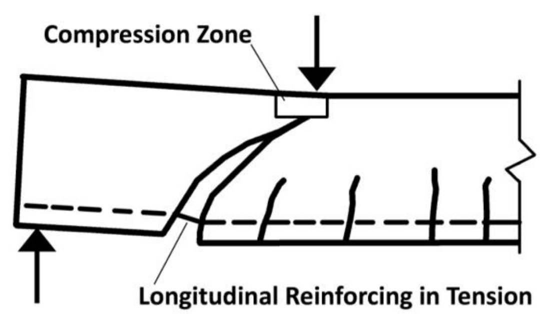

Figure 3: Shear-Compression Failure

The failure type is not solely determined from the geometry of the member. The longitudinal reinforcing ratio, ρ; the member depth, D; and the concrete compressive strength, f_c'; all play a role in the determination of the shear strength of the member and the failure mode that occurs.

CURRENT CODE EVALUATION APPROACH

This discussion is focused on the OOP strength of one-way walls and slabs. Traditionally, the OOP capacity of walls and slabs has been determined using the procedures laid out in the commercial concrete building code ACI 318 (2015) and the nuclear concrete building code ACI 349 (2014). ACI 349-13 predominately references ACI 318-08 for the determination of most concrete capacities, including the OOP shear capacity of walls and beams. ACI 318-08 (2015) does not provide a specific recommendation for the calculation of the OOP shear capacity of walls. Therefore, the evaluation follows the basic approach for the calculation of element shear capacities where the nominal shear strength is ACI 318-08 Equation 11-2:

$$V_n = V_c + V_s \tag{1}$$

Where V_c and V_s are the contribution of concrete and steel reinforcing strengths, respectively. For wall sections without OOP transverse reinforcing, $V_s = 0$. Therefore, the entire capacity is based on the concrete section shear strength, V_c. This shear capacity is simply the classic shear strength equation, ACI 318-08 Equation 11-3:

$$V_c = 2\sqrt{f_c'} \times b_w \times d \tag{2}$$

For the OOP shear capacity of a wall, a unit width, $b_w = 1$ ft, is assumed to calculate the OOP shear capacity on a per foot basis.

CONCRETE BEAM TEST DATABASES

The data for the shear tests on RC beams was compiled and presented by Reineck et al. in multiple publications (2006, 2010, and 2012). The database compiled in these publications contains 1365 shear tests on beams without transverse reinforcing. The database was split into two separate databases, vuct-RC-DK-sl (Reineck et al, 2013) for slender beams with $a/d \geq 2.4$; and vuct-RC-DK-24 for non-slender beams with $a/d < 2.4$ (Reineck and Todisco, 2014). The primary intent of the databases is to collect the RC beam data and, thus, no specific recommendations are provided in the summary papers on how to adjust the code-based shear capacity calculation. The Reineck papers do point out the current approach in ACI 318 used to determine the shear strengths of members without transverse reinforcement does not adequately consider all parameters and, in specific scenarios, can be unconservative.

Figures 4, 5, and 6 below plot the ratio of the tested shear capacity, V_{test}, over the ACI nominal shear capacity calculated by ACI 318-08 Equation 11-3, V_{nACI}, on the vertical axis against several parameters of interest on the horizontal axis. The solid red line at the 1.0 on the vertical axis on all three charts represents the case where the test data meets the ACI 318-08 nominal shear strength. Thus, test points above this red line represent tests which exhibit higher shear capacity than the ACI code nominal provisions, while tests below the red line represent tests which exhibit lower shear capacity than the ACI code nominal provisions. The parameters on the horizontal axis are d, ρ, and a/d. The slender data is plotted in orange and the non-slender data is plotted in blue.

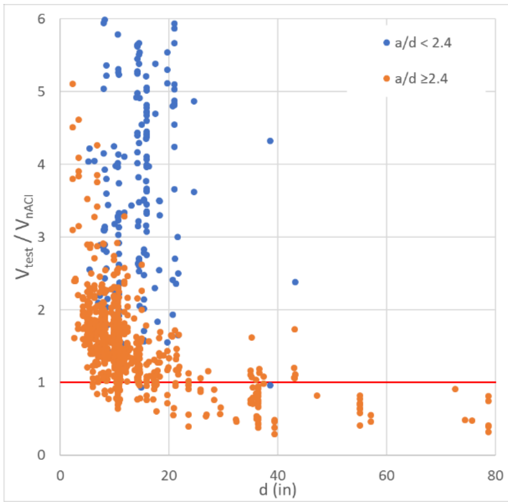

Figure 4: Test to Code Ratio versus Effective Beam Depth, d

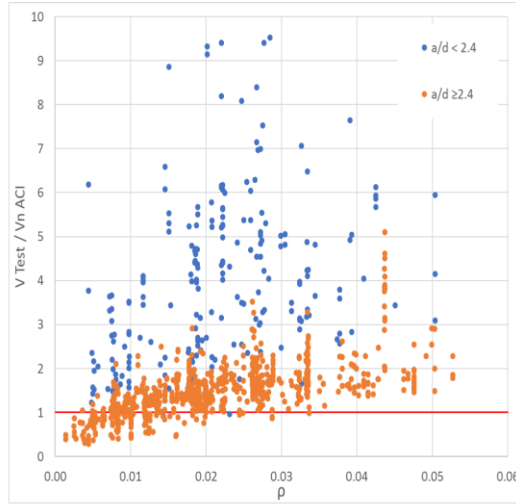

Figure 5: Test to Code Ratio versus Reinforcing Ratio, ρ

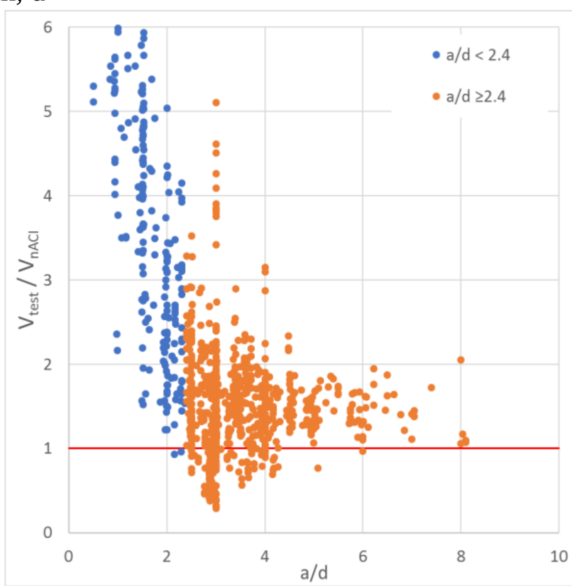

Figure 6: Test to Code Ratio versus Shear Span Ratio, a/d

There are some key relationships/conclusions that are evident from the plotted data:

- The shear strength of slender beams has a strong dependency on d and ρ. The code equation tends to underpredict the shear strength for deeper slender members and those members with low longitudinal reinforcing ratios. For shallow members and those with larger amounts of longitudinal reinforcing, the code equation is conservative.
- The shear strength of non-slender beams exhibits more scatter in the plots against d and ρ. The shear capacity of non-slender members does not appear to be as heavily influenced by these parameters
- The shear strength of non-slender beams has a strong dependency on the shear span ratio. The shorter the shear span, the higher the shear capacity.

- The shear strength of non-slender beams does not show a strong dependence on shear span ratio.

UPCOMING CODE REVISIONS

There are proposed code changes in both ACI 318 and ASCE 43 that are providing updated equations to incorporate the information from the RC beam shear test databases. ACI's changes have not yet been published. An article in Concrete International, Proposals for New One-Way Shear Equations for the 318 Building Code (Belarbi et al, 2017) presents six different proposals to calculate the one-way shear capacity of beams, but the article does not provide the final method developed by ACI. The method is reported to contain aspects of each of the proposed approaches.

The changes proposed in ASCE 43 are in the final stages of approval and are likely to appear in the next edition of ASCE 43 (2017). The proposed equation has the form:

$$K = \frac{2.8\sqrt[4]{100\rho}}{\sqrt{d}} \tag{3}$$

Where K is a size correction factor to be multiplied by the shear capacity determined by equation (2). This is only to be applied for members without minimum shear reinforcement and is limited to members greater than 5 inches deep.

The dependency on d and ρ are captured in this equation. However, there is no dependency on the shear span ratio. This is due to the dataset used in the development of the equation. While not stated in the code, the equation was developed solely using the slender database. The equation does not consider the non-slender dataset. This is likely due to the fact that non-slender beams are typically designed using other approaches (e.g. strut and tie) than the traditional shear equation. Therefore, the code authors decided that the inclusion of the data was not warranted. However, the equation places no limitation on when it's use is appropriate. Therefore, for the calculation of the OOP shear capacity of a wall, the equation would still apply for both slender and non-slender beams. For the evaluation of the OOP shear capacity of a non-slender wall, strut and tie methodology is typically not applied, or feasible. Thus, the engineer is limited to using this equation above with the resulting size correction factor.

Since the proposed ASCE 43 approach has been developed using the slender data, the developed equation may be appropriate for slender elements. However, for non-slender data (nuclear plant shear wall structures would typically fall into this range) the equation may lead to overly conservative reductions. Table 1 presents some example correction factors developed for typical walls found in nuclear-type structures.

Table 1: Example Size Correction Factors, K

a/d	ρ	d (in)	K
1.43	0.80%	56	0.35
1.29	0.30%	62	0.26
1.09	0.30%	68	0.25
1.57	0.20%	56	0.25
1.78	0.30%	68	0.25
1.10	0.20%	68	0.23
1.79	0.30%	68	0.25
1.89	0.20%	53	0.26

As shown in the table, the size correction factor for these example walls would be as low as 0.25, a significant reduction from the design capacity from Equation 11-2. Based on Figure 6, it would be anticipated the nominal OOP shear capacity would be at least equal to, if not greater than the basic code equation.

This is further demonstrated in plots of the ratio of the tested shear capacity, V_{test}, over the ACI nominal shear capacity modified by the proposed K factor, K * V_{nACI}. Figures 7, 8, and 9 plot the ratio against d, ρ, and a/d respectively.

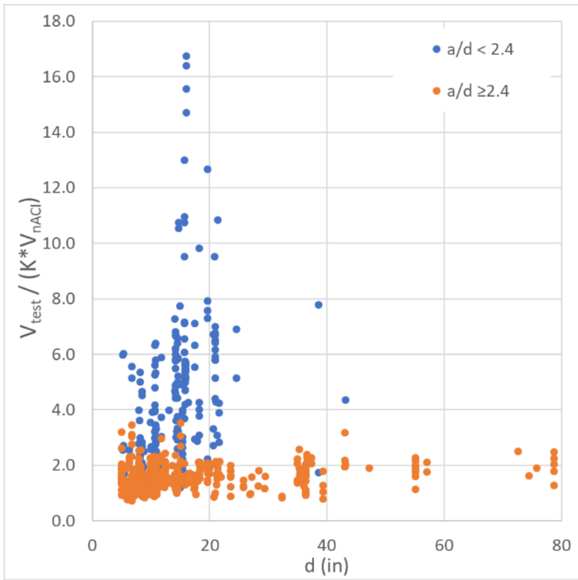

Figure 7: Test to Modified Code Ratio versus Effective Beam Depth, d

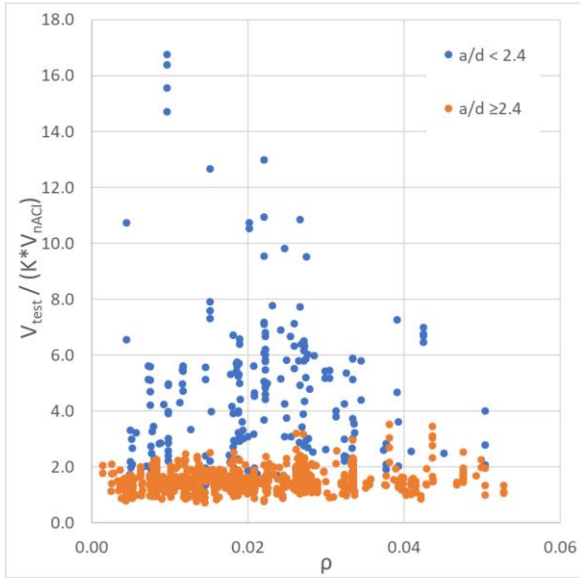

Figure 8: Test to Modified Code Ratio versus Reinforcing Ratio, ρ

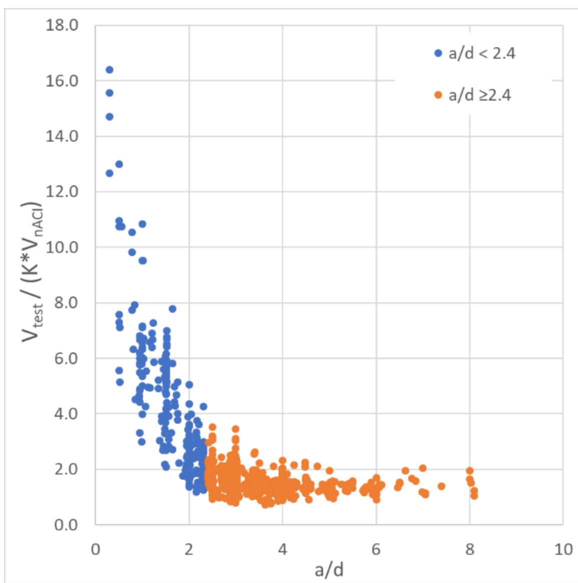

Figure 9: Test to Modified Code Ratio versus Shear Span Ratio, a/d

As shown in the figures, the ratio of the tested capacity versus the modified code-based shear capacity is relatively consistent for slender members, a/d >2.4. However, for non-slender members, the proposed correction factor does not provide a consistent result and may be significantly conservative. This is more apparent in Figure 9, where for low a/d ratios, the modified code-based capacity is significantly less than the tested capacity. This demonstrates that additional modifications are needed to capture potential reduction factors for non-slender members.

PROPOSED APPROACH

The approach being implemented in this EPRI study incorporates both the slender and non-slender data to cover a wider range of applicable data. Dr. Robert Kennedy in a "Statistical Analysis of the Shear Strength of Reinforced Concrete Beams" (1967) developed a similar approach for the determination of shear capacity but used a much smaller dataset. In Kennedy's approach two equations are developed, one for the diagonal tension failure shear capacity, and one for the shear-compression failure capacity. For a given section, both shear capacities are calculated and the larger of the two capacities is the controlling shear capacity. For non-slender members, the shear compression failure mode controls. The diagonal crack due to diagonal tension must first form to engage the shear compression mechanism shown in Figure 3. After this mechanism occurs, the shear capacity can continue to increase to the point of the compression zone failure. For slender members the diagonal tension capacity tends to control. The resulting diagonal crack passes through the entire section and does not allow the compression zone to form.

The approach developed by Dr. Kennedy does not rely on a hard break for the shear span ratio to define whether one equation or the other is used to calculate the shear capacity. There is a transition zone between shear compression and diagonal tension and that zone cannot be characterized by a single value of shear span. Dr. Kennedy's method developed a more complex approach for the controlling capacity to be determined.

The current proposed ASCE 43 correction factor essentially is only considering diagonal tension failure.

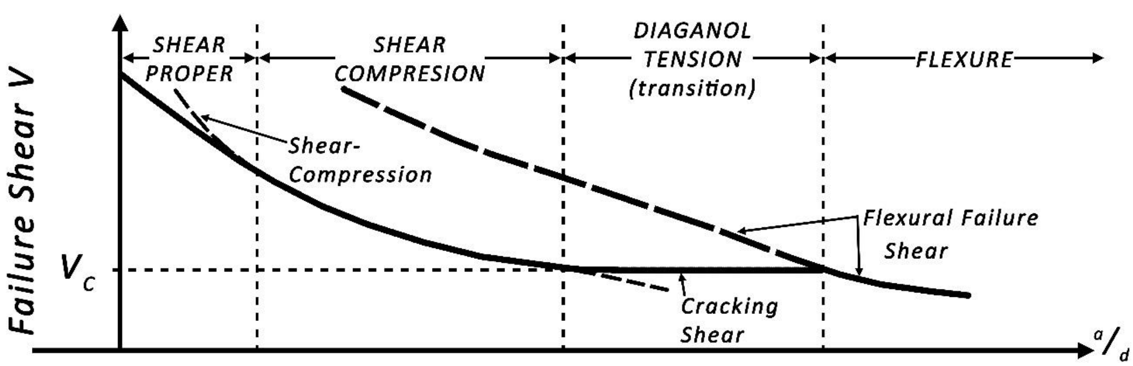

Figure 10. Relationship Between Modes of Failure for Simple-Supported Beams

For the EPRI study, Kennedy's approach is used, but with the larger set of shear data from ACI. The data regression to calculate the two shear capacity equations incorporates the same factors, ρ and d, as the proposed ASCE correction factor but also considers the shear span ratio, a/d, and the concrete compression capacity, f_c', directly. This approach results in a full shear capacity equation and does not act as a modifier to the current code capacity.

CONCLUSIONS

The out of plane shear strength of reinforced concrete walls and slabs have not been accurately characterized over all ranges of beams/slabs in the current version of the ACI and ASCE structural codes. Efforts have been ongoing to address this lack of accurate capacity characterization for several years and both the ACI and ASCE codes are expected to be updated in the near future. However, these proposed changes are only based on a portion of the available test data and do not accurately characterize the shear capacity of non-slender beams. Nuclear structures are particularly affected by this limitation and use of these proposed new equations could lead to overly conservative capacities.

EPRI is in the process of conducting a detailed assessment of the entire set of test data. The approach being taken will allow for the prediction of the controlling failure mode of the beam section (diagonal tension or shear compression), which will reduce the uncertainty in the resulting seismic fragilities recommended for SPRAs. Recommended equations for median capacities along with recommended uncertainties are expected to be developed by the end of 2019. Preliminary findings show that using this approach with the larger ACI shear test dataset will provide a more realistic (less conservative) characterization of the shear capacity of members without transverse reinforcing for use in seismic margin and seismic fragility calculations.

REFERENCES

American Concrete Institute (2015), "Building Code Requirements for Structural Concrete and Commentary," *ACI 318-14, 2nd printing*, Farmington Hills, MI.

American Concrete Institute (2014), "Code Requirements for Nuclear Safety-Related Concrete Structures," *ACI 349-13, 1st printing*, Farmington Hills, MI.

American Society of Civil Engineers (2017), "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," *ASCE/SEI 43-Draft*.

Belarbi, A., Kuchma, D.A., and Sanders, D.H. (2017), "Proposals for New One-Way Shear Equations for the 318 Building Code," *Concrete International*, Vol. 39 No.9.

Joint ASCE-ACI Task Committee 426, (1973), "The Shear Strength of Reinforced Concrete Members," Journal of the Structural Division, ST6.

Kennedy, R. (1967), *A Statistical Analysis of the Shear Strength of Reinforced Concrete Beams*, Stanford University.

Reineck, K.-H.; Bentz, E. C.; Fitik, B.; Kuchma, D. A.; and Bayrak, O. (2013), "ACI-DAfStb Database of Shear Tests on Slender Reinforced Concrete Beams without Stirrups," *ACI Structural Journal*, 110-S72.

Reineck, K.-H.; Kuchma, D. A.; and Fitik, B. (2006), "Erweiterte Datenbanken zur Überprüfung der Querkraftbemessung von Konstruktionsbetonbauteilen ohne und mit Bügel (Extended Databases with Shear Tests on Structural Concrete Beams without and with Stirrups for Assessing Shear Design Procedures)," *Research Report, ILEK*, University of Stuttgart, Stuttgart, Germany. (in German).

Reineck, K.-H.; Kuchma, D. A.; and Fitik, B. (2010), "Extended Databases with Shear Tests on Structural Concrete Beams without and with Stirrups for the Assessment of Shear Design Procedures," *Research Report, ILEK*, University of Stuttgart and University of Illinois-Champaign, Urbana, IL.

Reineck, K.-H.; Kuchma, D. A.; and Fitik, B.(2012), "Erweiterte Datenbanken zur Überprüfung der Querkraftbemessung von Konstruktionsbetonbauteilen ohne und mit Bügel (Extended Databases with Shear Tests on Structural Concrete Beams without and with Stirrups for Assessing Shear Design Procedures)," *DAfStb H. 597*, Beuth Verl, Berlin, Germany. (in German).

Reineck, K.-H. and Todisco, L. (2014), Database of Shear Tests for Non-Slender Reinforced Concrete Beams without Stirrups, *ACI Structural Journal*, 111-S116.