JOINT SHEAR BEHAVIOR PREDICTION IN RC BEAM-COLUMN CONNECTIONS SUBJECTED TO SEISMIC LATERAL LOADING

Jaehong Kim[1] and James M. LaFave[2]

[1] *Structural Consultant, S.K. Ghosh Associates Inc., Palatine, IL, U.S.A.*
[2] *Associate Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, U.S.A.*
Email: jkimstructure@gmail.com, jlafave@illinois.edu

ABSTRACT:

An extensive database of reinforced concrete (RC) beam-column connection test specimens exhibiting joint shear failure when subjected to reverse cyclic lateral loading (341 experimental subassemblies in total from all over the world) was constructed and classified by governing failure mode sequence, in-plane geometry, out-of-plane geometry, and joint eccentricity. The included subassemblies were constructed at above one-third scale, and they all used conventional types of reinforcement anchorage. Adequate joint confinement was found to be maintained when the provided amount of joint transverse reinforcement was equal to or above a certain limit. Possible influence parameters on the maximum response (in terms of both stress and strain, and thus also average stiffness) of RC joint shear behavior are first introduced. Then, RC joint shear strength and deformation models, which are applicable across diverse types of RC beam-column connections, are suggested by employing a Bayesian parameter estimation method. The suggested joint shear strength and deformation models indicate that RC joint shear (stress and strain) capacity under reverse cyclic (seismic) lateral loading is mainly dependent on concrete compressive strength, in-plane geometry, out-of-plane geometry, joint eccentricity, beam reinforcement, and joint transverse reinforcement. Finally, key parameter effects on the maximum response of RC joint shear behavior are discussed.

KEYWORDS: Reinforced concrete connection, Joint shear capacity, Experimental database, Bayesian parameter estimation method

1. INTRODUCTION

Reinforced concrete (RC) beam-column connections have been identified as potentially one of the weaker components when a reinforced concrete moment frame is the main Seismic Force Resisting System (SFRS). Numerous experimental and analytical studies have been performed since the mid-1960s to clarify the performance of RC beam-column connections subjected to seismic lateral loading. These studies identified that understanding joint shear behavior is important toward maintaining reasonable and ductile behavior, which is one of the most important factors in current seismic design philosophies for RC beam-column connections.

Hanson and Connor (1967) first defined joint shear demand that is determined from a free-body diagram at the mid-height of a joint panel. Paulay et al. (1978) suggested qualitative joint shear resistance mechanisms, which can consist of a concrete strut and/or a truss. The concrete strut mechanism is formed from resisting the transferred force by concrete compression zones of adjacent beam(s) and column(s), whereas the concrete truss mechanism is formed from resisting the transferred force via bond between reinforcement and surrounding concrete within the joint panel.

ACI 318-05, ACI 352R-02, AIJ 1999, and NZS 3101:1995 have each suggested their own RC joint shear strength definition through extensive experimental and analytical investigation. All of these provisions consider that joint shear strength is dependent on concrete compressive strength and that it is also a function of connection geometry. However, these provisions define the amount of the contribution from concrete compressive strength to joint shear strength in different manners; the power term of concrete compressive strength is 0.5 in the ACI approaches, 0.7 in the AIJ 1999, and 1.0 in the NZS 3101:1995.

Some examination about influence parameters on RC joint shear strength (which has often been performed by collecting experimental results), and suggestion of RC joint shear strength models (which have been derived by employing diverse analytical approaches), has already been conducted. For example, analytical procedures for predicting RC joint shear behavior have been proposed in conjunction with existing shear stress vs. shear strain prediction models such as the modified compression field theory (Youssef and Ghobarah 2001, Lowes and Altoontash 2003, and Shin and LaFave 2004). And recently, RC joint shear behavior has been predicted by assuming that joint shear is transferred into a joint panel via assumed struts (Parra-Montesinos and Wight 2002 and Mitra and Lowes 2007). In spite of the extensive prior research, there has still been no consensus on the effect of some parameters and also on a generally accepted model for RC joint shear behavior.

Kim et al. (2007) established a procedure to develop an RC joint shear strength model using a basic dataset of experiments that maintained proper joint confinement and had no out-of-plane members and no joint eccentricity, by employing a Bayesian parameter estimation method. More recently, Kim and LaFave (2008) suggested RC joint shear strength models for design of various modern types (i.e., with no issues due to insufficient joint confinement) of RC beam-column connections. In this study, RC joint shear strength models for both modern and older types of beam-column connections have been constructed. Because knowledge about joint shear deformation, as well as about joint shear strength, is required to maintain appropriately ductile response of RC beam-column connections, prediction models for joint shear deformation have also been proposed. Finally, key parameter affects on RC joint shear peak behavior are discussed using the developed RC joint shear strength and deformation models.

2. EXPERIMENTAL DATABASE

The experimental database of RC beam-column connections originally constructed by Kim and LaFave (2008) has been further expanded for this research. This database of RC beam-column connection subassemblies has been constructed under a consistent set of criteria. All specimens were subjected to quasi-static cyclic lateral loading and their final governing modes were joint shear failure (either in conjunction with or without yielding of beam reinforcement). The database only included subassemblies with conventional types of reinforcement anchorage (no headed bars or anchorage plates), and all longitudinal beam and column reinforcement are deformed bars. Finally, the closed hoops and cross-ties for joint transverse reinforcement generally met the detailing recommendations of ACI 352R-02, accounting for subassembly scale.

The finally constructed database includes 341 experimental test results. Within this total database, 182 of the 341 cases had equal to or above 0.70 in A_{sh} ratio (provided-to-recommended amount of joint transverse reinforcement per ACI 352R-02), which is referred to as the reduced dataset that contains only test specimens maintaining sufficient joint confinement. Within the reduced dataset, the number of subassemblies without out-of-plane members and without joint eccentricity is 136 (referred to as the basic dataset), while the number of subassemblies with out-of-plane members and without joint eccentricity is 30 (24 interior and 6 exterior joints) and the number with eccentricity (with or without out-of-plane members) is 16 (all of them interior joints). Within the basic dataset, the numbers of interior, exterior, and knee joints are 78, 48, and 10, respectively.

3. RC JOINT SHEAR STRENGTH MODELS

Probabilistic methodology such as the Bayesian parameter estimation method has been employed to develop capacity prediction models for RC beam and column members. Gardoni et al. (2002) developed probabilistic models for the shear capacity of RC columns by correcting the biases in existing deterministic models and by quantifying remaining errors; that is:

$$C(\mathbf{x},\Theta) = c_d(\mathbf{x}) + \gamma(\mathbf{x},\theta) + \sigma\varepsilon \quad (3.1)$$

In Eqn. 3.1, $\mathbf{x}$ is the vector of input parameters that were measured during tests, $\Theta = (\theta, \sigma)$ denotes the set of unknown model parameters that are introduced to fit the model to the test results, $c_d(\mathbf{x})$ is an existing deterministic model, $\gamma(\mathbf{x}, \theta)$ is the bias–correction term, ε is the normal random variable with zero mean and unit variance, and finally σ is the unknown model parameter representing the magnitude of model error that remains after bias-correction. The natural logarithm is employed to Eqn. 3.1 to satisfy that the variance of model error is independent of the input parameter $\mathbf{x}$; that is:

$$\ln[C(\mathbf{x}, \Theta)] = \ln[c_d(\mathbf{x})] + \sum_{i=1}^{p} \theta_i h_i(\mathbf{x}) + \sigma\varepsilon \tag{3.2}$$

in which $h_i(\mathbf{x})$, i = 1,…,p, denote "explanatory" functions of input parameter $\mathbf{x}$ that are introduced based on knowledge about the capacity of the target structure. A Bayesian parameter estimation method was then employed to find uncertain parameters that make the models in Eqn. 3.2 best fit the test results.

Recently, Song et al. (2007) constructed RC beam shear strength models without relying on an existing deterministic model; that is:

$$\ln[C(\mathbf{x}, \Theta)] = \sum_{i=1}^{p} \theta_i h_i(\mathbf{x}) + \sigma\varepsilon \tag{3.3}$$

After Bayesian updating, the posterior mean values of θ_i are substituted in for θ_i in Eqn. 3.3 to obtain a capacity model. The posterior mean of σ is used to quantify the magnitude of the remaining model error.

Kim et al. (2007) and Kim and LaFave (2008) developed preliminary RC joint shear strength models employing Eqn. 3.3. By using Eqn. 3.3, they found the quantitative contribution and explicit significance of various examined parameters on RC joint shear strength without being limited by current existing deterministic models. Kim et al. (2007) first constructed an RC joint shear strength model using the basic dataset by employing eight parameters: (1) concrete compressive strength; (2) in-plane geometry (JP: 1.0 for interior, 0.75 for exterior, and 0.5 for knee connections); (3) beam-to-column width ratio (b_b/b_c); (4) beam height to column depth ratio (h_b/h_c); (5) beam reinforcement index, BI, defined as $(\rho_b \times f_{yb})/f'_c$ in which ρ_b is the beam reinforcement ratio and f_{yb} is the yield stress of beam reinforcement; (6) joint transverse reinforcement index, JI, defined as $(\rho_j \times f_{yj})/f'_c$ in which ρ_j is the joint transverse reinforcement ratio and f_{yj} is the yield stress of joint transverse reinforcement; (7) A_{sh} ratio (provided-to-recommended amount of joint transverse reinforcement per ACI 352R-02); and (8) spacing ratio (provided-to-recommended spacing of joint transverse reinforcement per ACI 352R-02). Then, Kim and LaFave (2008) suggested a joint shear strength model, based on the reduced dataset, for various modern types of RC beam-column connections by introducing two additional parameters – out-of-plane geometry, TB, (1.0 for subassemblies with zero or one transverse beams, and 1.2 for subassemblies with two transverse beams), as well as joint eccentricity ($1\text{-}e/b_c$, where e is the distance between the centerline of the beam and that of the column).

For both modern and older types of RC beam-column connections, RC joint shear strength models have been developed using the total database by employing the same parameters and procedures introduced by Kim and LaFave (2008). The Bayesian parameter estimation method indicates that concrete compressive strength, beam reinforcement index, joint transverse reinforcement index, in-plane geometry, out-of-plane geometry, and joint eccentricity are more important than other parameters in determining joint shear strength (v_j). Eqn. 3.4 is the constructed joint shear strength model only considering key parameters, and it yields σ of 0.151.

$$v_j(\mathrm{MPa}) = 1.21(\mathrm{TB})^{0.981}\left(1-\frac{e}{b_c}\right)^{0.679}(\mathrm{JI})^{0.136}(\mathrm{BI})^{0.301}(\mathrm{JP})^{1.33}\left(f'_c\right)^{0.764} \tag{3.4}$$

Concrete compressive strength is the most important parameter in determining RC joint shear strength, perhaps in part because it is related to both the concrete strut and truss mechanisms that may be activated to resist the induced RC joint shear demand. The contribution of concrete compressive strength is most accurately described when its power term is around 0.75. If in-plane geometry is the only variable, the joint shear strengths of exterior and knee joints are around 70% and 40% of interior joints, respectively. Compared to the developed joint shear strength model by Kim and LaFave (2008), Eqn. 3.4 shows that the role of joint transverse reinforcement is more activated in the determination of RC joint shear strength after including test results of subassemblies with insufficient joint confinement.

A simple RC joint shear strength model, which is applicable to both modern and older types of RC beam-column connection subassemblies, can then be suggested based on Eqn. 3.4; that is:

$$v_j(\mathrm{MPa}) = \alpha_t\,\beta_t\,\eta_t\lambda_t\,(JI)^{0.15}\,(BI)^{0.30}\left(f_c'\right)^{0.75} \tag{3.5}$$

In Eqn. 3.5, α_t is the in-plane geometry parameter (1.0 for interior, 0.7 for exterior, and 0.4 for knee connections); β_t is the out-of-plane geometry parameter (1.0 for subassemblies with zero or one transverse beam, and 1.2 for subassemblies with two transverse beams); η_t is the joint eccentricity parameter ($= \left(1 - e/b_c\right)^{0.67}$); and λ_t is 1.31 (an adjusting factor to set the overall average of the ratios of Eqn. 3.5 to Eqn. 3.4 as 1.0).

Eqn. 3.2 can be expressed as Eqn. 3.6 by introducing a constant bias-correction term θ (Song et al. 2007), and Eqn. 3.6 was used in an attempt to evaluate the overall bias and scatter of Eqn. 3.5.

$$\ln[C(\mathbf{x},\Theta)] = \ln[c_d(\mathbf{x})] + \theta + \sigma\varepsilon \tag{3.6}$$

Deterministic joint shear strength is less biased when the posterior mean of θ is more close to zero, and it has less scatter when the posterior mean of σ is smaller. When Eqn. 3.5 is used as a deterministic model $c_d(\mathbf{x})$ in Eqn. 3.6, the posterior means of θ and σ are –0.011 and 0.153, respectively. Thus, the suggested Eqn. 3.5 can be considered as an unbiased RC joint shear strength expression that maintains a similar level of prediction accuracy to that of Eqn. 3.4. This finding is confirmed by plotting experimental joint shear stress vs. joint shear strength defined by Eqn. 3.5, as shown in Figure 3.1. This simple and unified RC joint shear strength model (Eqn. 3.5) is recommended for practical evaluation and designs of both older and modern types of RC beam-column connections, perhaps after adjusting its value downward for increased safety.

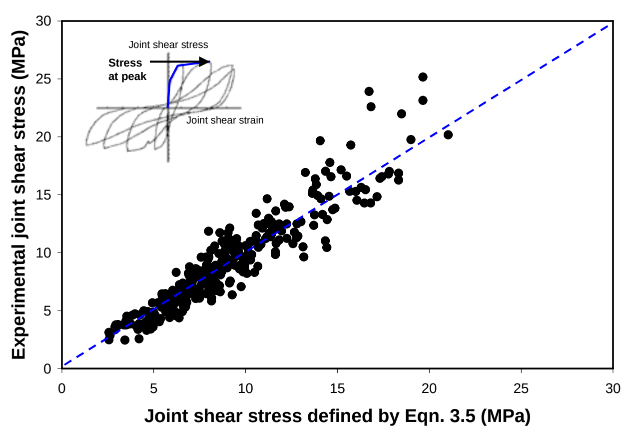


Figure 3.1: Experimental joint shear stress vs. Joint shear stress model (Eqn. 3.5)

4. RC JOINT SHEAR DEFORMATION MODELS

RC joint shear deformation models (at peak response) have also been constructed based on following the same procedure established to develop RC joint shear strength models. In the basic dataset, 56 of 136 cases provided experimental information about joint shear strain. As explained by Kim and LaFave (2007), joint shear strain has quite a strong relationship to concrete compressive strength in "J" failures (joint shear failure before yielding of longitudinal reinforcement); on the other hand, it does not show any specific tendency to concrete compressive strength in "BJ" failures (joint shear failures after yielding of longitudinal reinforcement). To remove the effect due to different governing failure mode sequence, joint shear strain is normalized by beam reinforcement index in developing joint shear strain prediction models; BI is the best parameter to discern between "J" and "BJ" failures. The joint shear strength model value divided by concrete compressive strength is also included as an explanatory term to improve the performance of the joint shear deformation models. The values for a joint shear deformation in-plane geometry parameter (JPR) can be determined by trial and error to have the strongest linear relationship based on plots of normalized joint shear strain (joint shear strain to BI) vs. normalized joint shear stress (joint shear stress to concrete compressive strength); the values of JPR are 1.0, 0.59, and 0.32 for interior, exterior, and knee connections, respectively.

Normalized joint shear strain models have first been constructed for the basic dataset by employing seven parameters: (1) normalized joint shear stress model (v_j/f'_c); (2) in-plane geometry (JPR); (3) joint transverse reinforcement index (JI); (4) beam-to-column width ratio (b_b/b_c); (5) beam height to column depth ratio (h_b/h_c); (6) A_{sh} ratio (provided-to-recommended amount of joint transverse reinforcement per ACI 352R-02); and (7) spacing ratio (provided-to-recommended spacing of joint transverse reinforcement per ACI 352R-02). In the reduced dataset, 84 of 182 cases provided experimental information about joint shear strain. Same as for the development of a joint shear strength model, out-of-plane geometry and joint eccentricity were included when developing a joint shear strength model for this dataset.

Finally, RC joint shear deformation models for the total database have been developed. Within the total database, 155 cases provided experimental information about joint shear deformation. A new in-plane geometry parameter "JPRU" is introduced to consider the effect of insufficient joint confinement on RC joint shear deformation. Values of JPRU are determined by multiplying JPR and an additional reduction factor 0.833 that is decided by trial and error to have the strongest linear relation in a plot of experimental joint shear strain normalized by BI vs. joint shear strength model normalized by concrete compressive strength. For the total database, the Bayesian parameter estimation method shows that in-plane geometry, joint shear strength model to concrete compressive strength, out-of-plane geometry, joint transverse reinforcement, and joint eccentricity are more important than other parameters in determining RC joint shear deformation capacity (γ_j). Eqn. 4.1 is the constructed joint shear deformation model only considering the key parameters, and it results in 0.401 for σ.

$$\gamma\,(\mathrm{Rad}) = 0.00565\,\mathrm{BI}\left(1-\frac{e}{b_c}\right)^{-0.628}(\mathrm{JI})^{0.0982}\,(\mathrm{TB})^{1.85}\left(\frac{v_j(\mathrm{Eqn.}(3.4))}{f'_c}\right)^{-1.73}(\mathrm{JPRU})^{2.11} \tag{4.1}$$

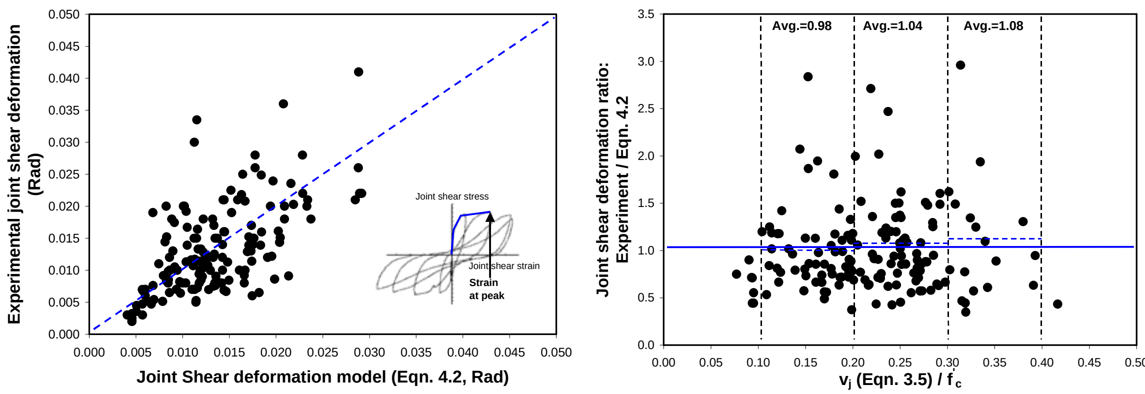
The magnitude of model error for joint shear deformation is distinctively greater than that for joint shear strength, in part because measured joint shear deformation naturally has larger uncertainty compared to measured joint shear strength (as a function of how each is measured during testing). This model has been simplified to a final unified joint shear deformation model; that is:

$$\gamma\,(\mathrm{Rad}) = \alpha_{\gamma t}\,\beta_{\gamma t}\,\eta_{\gamma t}\,\lambda_{\gamma t}\,\mathrm{BI}\,(\mathrm{JI})^{0.10}\left(\frac{v_j(\mathrm{Eqn.}(3.5))}{f'_c}\right)^{-1.75} \tag{4.2}$$

in which, $\alpha_{\gamma t}$ is the in-plane geometry parameter (= $(\mathrm{JPRU})^{2.10}$); $\beta_{\gamma t}$ is the out-of-plane geometry parameter

(1.0 for subassemblies with zero or one transverse beam, and 1.4 for subassemblies with two transverse beams); $\eta_{\gamma t}$ is the joint eccentricity parameter (= $(1-e/b_c)^{-0.60}$); and $\lambda_{\gamma t}$ is 0.00549 (an adjusting factor to set the overall average of the ratios of Eqn. 4.2 to Eqn. 4.1 as 1.0).

The overall bias and scatter of Eqn. 4.2 has also been evaluated by employing Eqn. 3.6; the posterior means of θ and σ are –0.0811 and 0.410, respectively. As shown in Figure 4.1(a), plotting experimental joint shear deformation vs. Eqn. 4.2 confirms that the suggested simple and unified model can determine joint shear deformation in an almost unbiased manner. Some local bias does still exist in certain subdivided ranges of the database. For example, Figure 4.1(b) plots joint shear strain ratio (experimental joint shear strain to Eqn. 4.2) vs. v_j (Eqn. 3.5)/f'_c that is a surviving parameter in the development of a joint shear strain model for the total database.



(a) Experimental shear strain vs. Eqn. 4.2 (b) Shear strain ratio vs. v_j (Eqn. 3.5)/f'_c

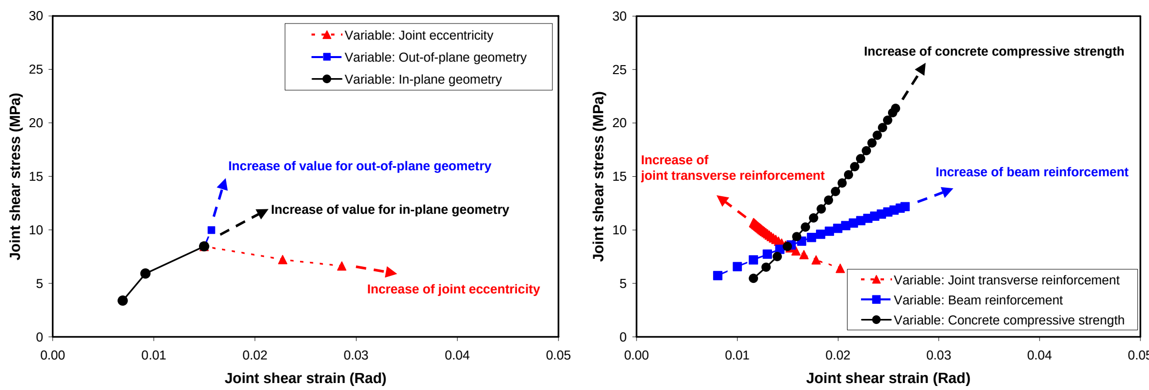
Figure 4.1: Simple and unified joint shear deformation model

5. PARAMETRIC EFFECTS ON JOINT SHEAR CAPACITY

The proposed simple and unified RC joint shear strength and deformation models indicate that concrete compressive strength, beam reinforcement, joint transverse reinforcement, in-plane geometry, out-of-plane geometry, and joint eccentricity are more informative than other parameters in determining RC joint shear capacity. At peak response, the influence of these parameters on RC joint shear stress vs. joint shear strain can be described using Eqns. 3.5 and 4.2. A standard configuration is first determined to examine the effects of these parameters on joint shear behavior. For the geometric conditions of this standard reference point, in-plane geometry is an interior connection (1.0 for JP and JPRU); out-of-plane geometry has no transverse beams (1.0 for TB); and joint eccentricity does not exist (1.0 for 1-e/b_c). For the non-geometric conditions, the median database values are simply used (34.0 MPa for concrete compressive strength, 0.054 for joint transverse reinforcement index (JI), and 0.32 for beam reinforcement index (BI)).

Figure 5.1(a) shows the influence of geometric parameters on peak RC joint shear stress vs. joint shear strain behavior based on the standard configuration. An increase of values for in-plane geometry or out-of-plane geometry results in an increase in both shear stress and shear strain at the peak; an increase of degree of joint eccentricity causes a decrease in shear stress and an increase in shear strain at the same time (i.e., decrease in joint shear stiffness). An increase of value for in-plane geometry or out-of-plane geometry means that RC beam-column connections have better geometry for resisting joint shear input demand. For example, when joint shear demand exceeds the capacity of RC joint shear resistance mechanisms, the joint panel rapidly expands in both the in-plane and out-of-plane directions. Thus, the existence of two transverse beams effectively provides passive confinement to the joint panel. When the centerline of beam member(s) does not coincide with the centerline of the column cross-section, the joint panel is subjected to torsion due to joint eccentricity, in addition to the shear force transferred from longitudinal beams. The weakened diagonal concrete strut and truss (joint shear resistance mechanisms) due to the generated torsion might trigger a reduction in joint shear stiffness.

Figure 5.1(b) shows the influence of non-geometric parameters on RC joint shear stress vs. joint shear strain behavior based on the standard configuration. An increase of concrete compressive strength or beam reinforcement results in an increase of both shear stress and shear strain simultaneously; an increase of joint transverse reinforcement causes an increase of joint shear stiffness. Because the capacity of both diagonal concrete strut and truss mechanisms is dependent on concrete compressive strength, joint shear stress vs. joint shear strain at the peak has a proportional relation to concrete compressive strength. Beam reinforcement index represents the relative confinement provided to the joint panel by in-plane beam reinforcement. More confinement at the top and bottom of the joint panel by longitudinal beam reinforcement strengthens joint shear resistance mechanisms. Joint transverse reinforcement index represents the relative confinement provided by joint transverse reinforcement within the joint panel. Because joint shear failure initiates an expansion of a joint panel in both the in-plane and out-of-plane directions, the improved confinement against the joint panel's expansion results in an increase in joint shear stiffness.



(a) Geometric parameters (b) Non-geometric parameters

Figure 5.1: Key parameter effects in the simple and unified joint shear capacity models

6. SUMMARY & CONCLUSIONS

An extensive experimental database (341 cases in total) for RC beam-column connections subjected to quasi-static lateral loading has been constructed by employing a consistent set of criteria such as governing failure mode (shear failure either in conjunction with or without yielding of beam reinforcement), scale (at least one-third), deformed bars (for longitudinal reinforcement), and anchorage type (no headed bars or anchorage plates). Based on this database, simple and unified RC joint shear strength and deformation models have been developed by the Bayesian parameter estimation method. The key findings are summarized as follows:

- Development of RC joint shear strength and deformation models identified that concrete compressive strength, beam reinforcement, joint transverse reinforcement, in-plane geometry, out-of-plane geometry, and joint eccentricity are more important than other parameters in determining joint shear capacity.

- Concrete compressive strength is the most important parameter in the determination of RC joint shear strength, and the accuracy of the model is maximized when the power term of concrete compressive strength is around 0.75. The inclusion of the suggested joint shear strength model normalized by concrete compressive strength leads to an improvement in the prediction accuracy of RC joint shear deformation models.

- The influence of key parameters on peak RC joint shear behavior has been investigated. An increase of the values for concrete compressive strength, in-plane geometry, out-of-plane geometry, and beam reinforcement results in an increase in both joint shear stress and strain. An increase of joint transverse reinforcement triggers an improvement in joint shear stiffness. On the other hand, an increase of the degree of joint eccentricity causes a reduction in joint shear stiffness.

REFERENCES

ACI-ASCE Committee 352. (2002). Recommendations for design of beam-column joints in monolithic reinforced concrete structures (ACI 352R-02). American Concrete Institute, Farmington Hills, Michigan, U.S.A.

ACI Committee 318. (2005). Building code requirements for structural concrete and commentary (ACI 318-05 / ACI 318R-05). American Concrete Institute, Farmington Hills, Michigan, U.S.A.

AIJ. (1999). Design guideline for earthquake resistance reinforced concrete buildings based on inelastic displacement concept (AIJ 1999). Architectural Institute of Japan, Tokyo, Japan.

Gardoni, P., Der Kiureghian, A., and Mosalam, K.M. (2002). Probabilistic capacity models and fragility estimate for reinforced concrete columns based on experimental observations. *Journal of Engineering Mechanics*, ASCE, **128: 10**, 1024-1038.

Hanson, N.W. and Connor, H.W. (1967). Seismic resistance of reinforced concrete beam-column joints. *Journal of Structural Division*, ASCE, **93: ST5**, 533-559.

Kim, J. and LaFave, J.M. (2007). Key influence parameters for the joint shear behaviour of reinforced concrete (RC) beam-column connections. *Engineering Structures*, 29:10, 2523-2539.

Kim, J., LaFave, J.M., and Song, J. (2007). A new statistical approach for joint shear strength determination of RC beam-column connections subjected to lateral earthquake loading. *Structural Engineering and Mechanics*, **27: 4**, 439-456.

Kim, J. and LaFave, J.M. (2008). Probabilistic joint shear strength models for design of RC beam-column connections. *ACI Structural Journal*, in-press.

Lowes, L.N. and Altoontash, A. (2003). Modeling reinforced-concrete beam-column joints subjected to cyclic loading. *Journal of Structural Engineering*, ASCE, **129:12**, 1286-1697.

Mitra, N. and Lowes, L.N. (2007). Evaluation, calibration, and verification of a reinforced concrete beam-column joint model. *Journal of Structural Engineering*, ASCE, **133:1**, 105-120.

NZS 3101: part 1. (1995). Concrete structures standard (NZS 3101:1995). Standard Association of New Zealand, Willington, New Zealand.

Parra-Montesinos, G.J. and Wight, J.K. (2002). Prediction of strength and shear distortion in R/C beam-column joints. *Behavior and design of concrete structures for seismic performance*, American Concrete Institute, **SP-197**, 191-214.

Paulay T., Park, R., and Priestley, M.J.N. (1978). Reinforced concrete beam-column joints under seismic actions. *ACI Journal*, **75: 11**, 585-593.

Shin, M. and LaFave, J.M. (2004). Modeling of cyclic joint shear deformation contribution in RC beam-column connections to overall frame behavior. Structural Engineering and Mechanics, **18:5**, 645-669.

Song, J., Kang, W.-H., Kim, K.S., and Jung, S. (2007). Probabilistic shear strength models for reinforced concrete beams by Bayesian updating based on experimental observation. *Proceedings of the 5th Conference on Computational Stochastic Mechanics*, Rodos, 623-632.

Youssef, M. and Ghobarah, A. (2001). Modeling of RC beam-column joints and structural walls. *Journal of Earthquake Engineeering*, **5:1**, 93-111.