



## INCORPORATING UNCERTAINTIES IN COMPONENT FAILURE MECHANISM IN SEISMIC ASSESSMENT OF RC BUILDINGS

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### ABSTRACT

Experimental data have shown that the seismic response and collapse risk of older-type multi-story buildings is highly influenced by the failure mechanism of its components, especially poorly-detailed gravity columns. Currently available methodologies for assessing collapse risk of RC buildings account for various sources of uncertainties in ground motion and epistemic uncertainties in the estimation of structural modelling parameters of RC components. Using available experimental data from cyclic tests on nominally identical RC columns, this study explores uncertainty in failure mode and how it influences seismic performance; thereby justifying the need to incorporate the treatment of this uncertainty when assessing collapse probability of columns and buildings. Based on a database of past experimental tests on RC columns, a probabilistic failure mode identification model is presented and the failure mode transition zone is identified. It is suggested that treatment of component failure mode uncertainties and its incorporation in a collapse risk assessment framework is essential for components in the failure mode transition zone.

Keywords: failure mode, deformation capacity, collapse risk, uncertainty, RC columns

### INTRODUCTION

Under seismic demands, RC columns of high-rise structures subjected to significant lateral displacements and are expected to dissipate seismic energy without losing their axial load carrying capacity. Post-earthquake reconnaissance reports (e.g. [1]-[2]) have attributed partial or total collapse of RC buildings, subjected to seismic actions, to the failure of gravity columns in these buildings. Under cyclic loading, RC columns exhibit one of three failure modes namely: flexure-dominated, flexure-shear dominated or brittle shear dominated modes. Brittle shear and flexure-shear dominated modes are characterized by shear distress prior to and after flexural yielding, respectively. Flexure failure mode is dominated by concrete crushing, bar buckling and/or bar fracture without formation of a diagonal failure plane. Typically, flexure-shear and brittle shear dominated columns have lower ductility capacities and lose their ability to dissipate seismic energy (Figure 1) and exhibit a faster rate of strength and stiffness degradation. Such components also have a higher likelihood of losing their gravity load bearing capacity, especially under significant axial load, potentially leading to building collapse at low deformation demands. Thus, from a seismic assessment perspective, identification of the probable damage mechanism provides a better insight on the likely performance of RC columns under seismic excitation and the consequence of failure.

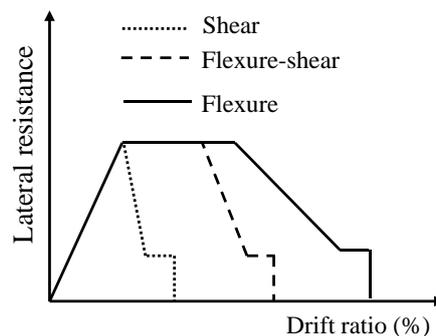


Figure 1. Backbone for different failure modes

Typically, capacity models in modern seismic assessment Standards [3] are first-order regression models and they do not adequately account for differences in damage mechanism with varying failure modes. Such models, even when applied in a probabilistic framework, may not effectively capture all uncertainties associated with the response of the components in the structure. Studies, such as Liel et al. [4], have demonstrated the influence of modelling uncertainties on the collapse risk of RC structures by considering uncertainty in structural modelling parameters and ground motion. However, experimental findings suggest that a probabilistic framework, especially at collapse limit state, needs to incorporate uncertainty in the damage mechanism of RC columns. Using a database of cyclic tests on RC columns, Zhu et al. [5]

described the existence of epistemic uncertainty associated with failure mode identification. Likewise, experimental tests on nominally identical RC columns [6]-[7] have shown that failure mode is inherently sensitive to loading conditions (displacement history and loading rate), which are not deterministic. These experimental tests also demonstrate the dependence of drift capacities at onset of loss of lateral strength and loss of axial capacity on failure mode.

In this paper, a case for the failure mode transition zone in RC columns is presented. Results of past experiments are reviewed to show how displacement history, strain rate and inherent material uncertainty can cause an unexpected failure mode switch or variation in damage mechanism in nominally identical reinforced concrete members, leading to variability in deformation capacity. The focus of this paper is to highlight the existence of failure mode uncertainties highlight the need for the treatment of these uncertainties. This study serves as an initial step towards a series of probabilistic studies on accounting for the influence of inherent uncertainty in local failure mode of RC columns on global collapse probability of older RC structures.

## **FAILURE MODE SWITCH IN RC COLUMNS**

### **Strain rate effect**

The influence of strain rate on response of RC members has been studied in various experimental programs. Research studies [7]-[8] have shown how increased strain rates can lead to a switch in failure mode from a flexure-dominated failure mode to a shear-dominated failure mode. Kulkarni and Shah [9], in a series of tests on RC beams, have also reported the switch from a shear-dominated response at a static strain rate to a flexure-dominated response at a dynamic strain rate. Seabold [8] concluded that the sensitivity of materials to strain rates can affect the behaviour of RC beams. Considering loading rate as a variable, Mutsuyoshi and Machida [7] conducted tests on nominally identical reinforced concrete columns. Experimental results showed that increased strain rates can cause a switch from a desirable flexure-dominated response to an unexpected flexure-shear dominated mechanism. Such an unexpected diagonal failure plane led to reduced ductility and lower energy dissipation in the column specimen.

Under high strain rates, there is an increase in yield strength of reinforcement and compressive strength of concrete. It is also noteworthy that experimental results from dynamic tests on concrete cylinders point to significant variability in compressive strength and ultimate strain [10]. The increase in material strength causes an increase in flexural and shear strength of RC components. However, it has an adverse effect on the cyclic degradation of strength and stiffness [11]. The increased rate of cyclic degradation of shear strength leads to a higher likelihood of flexure-shear interaction in RC columns under cyclic loading.

It is noteworthy that strain rate effect does not necessarily lead to a failure mode switch in all RC columns. Other experimental programs, i.e. Ghannoum et al. [12], did not observe a failure mode switch in their tests. This is probably due to the fact that the column specimens in these tests were not susceptible to failure mode switch (See discussion on failure mode transition zone later in this paper). Thus, there is need to identify the combination of material, loading, and geometric properties that can make a component susceptible to failure mode switch due to strain rate effects. This will be discussed subsequently in this paper.

### **Displacement history effect**

It is well understood that the seismic response of RC columns is sensitive to displacement history. There is an awareness that strength/stiffness decay, under cyclic loading, is dependent on the displacement history. Little focus, however, has been placed on how displacement history can cause a failure mode switch. Ranf et al [6] subjected six nominally identical columns to different displacement histories and concluded that while other specimens exhibited a flexure-shear dominated failure mode, one of the specimens exhibited a flexure-dominated response and had a larger drift ratio at failure than other specimens. Also, based on experimental output from two nominally identical columns subjected to a monotonic and cyclic loading protocol, Nakamura and Yoshimura [13] also concluded that displacement history influences the failure mode and collapse behaviour of RC columns. The column subjected to monotonic loading, had a less ductile damage mechanism and a drift at axial failure significantly, lower than the column subjected to cyclic loading, was reported.

The sensitivity of failure mode to displacement history effect is also likely in RC columns subjected to bidirectional lateral loading. By comparing experimental results of nominally identical circular bridge columns tested using unidirectional lateral loading and bidirectional lateral loading [14], it can be deduced that bidirectional loading can also cause an unfavourable switch in failure mode from a flexure-dominated failure mode to a flexure-shear dominated failure mode, leading to more severe degradation of stiffness and strength and subsequently a lower drift capacity.

### **Effect of inherent variability in material properties**

Past studies ([15], [16]) have discussed failure mode switch due to inherent uncertainty of material properties in RC beams. Typically, concrete exhibits more inherent uncertainty than steel. As shown in the study by Allen [15], the closer a beam is to being compression-controlled, the higher the likelihood of exhibiting a failure mode switch. In RC columns, the controlling parameter, concrete or steel, is dependent on axial load. RC columns subjected to axial load above balanced axial load ( $P_b$ ) are compression controlled and are influenced by concrete properties. Thus, influence of inherent material uncertainty in RC columns will be more pronounced in compression-controlled columns.

Evidence of failure mode switch in RC columns was reported in an experimental study on three non-ductile RC beam-column subassemblies carried out by Motter et al. [17] (Figure 2). The difference between the subassemblies was the spacing in joint reinforcement. The geometric properties, material properties, reinforcement detailing of the columns were nominally identical. The constant axial load on the three specimens was  $1.15P_b$ . Experimental results showed that failure was localized in the columns only and the load-displacement response was influenced by the variation in failure mode in the columns of the subassemblies (Figure 3). Using experimental data, the authors showed that the joint behavior did not have any influence on the response of the subassemblies. The failure mechanism of two of the columns was dominated by the formation of a diagonal failure plane and the lateral drifts at axial failure were 2.4% and 3% (Figure 4). The third column experienced a flexure-dominated failure mode and suffered axial failure at 4.85% drift ratio (Figure 5a). The authors concluded that the failure mode switch was most likely due to variability in concrete properties within and between columns of test specimens.

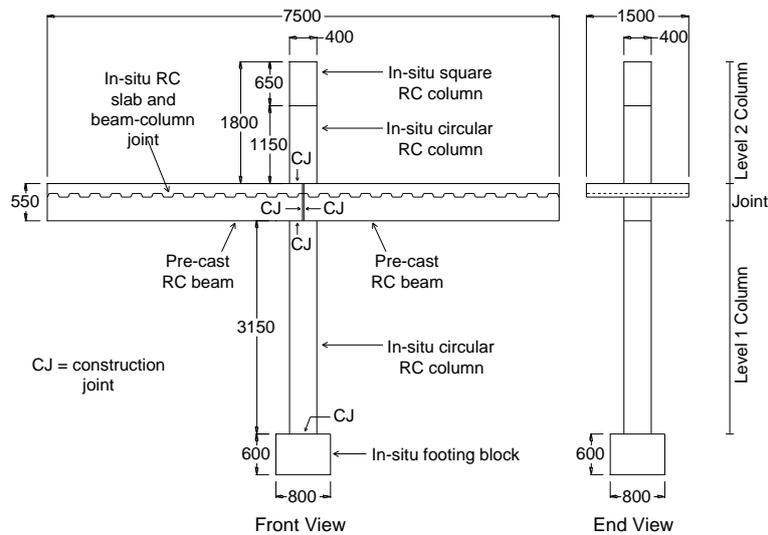


Figure 2. Details of beam-column subassemblies [17]

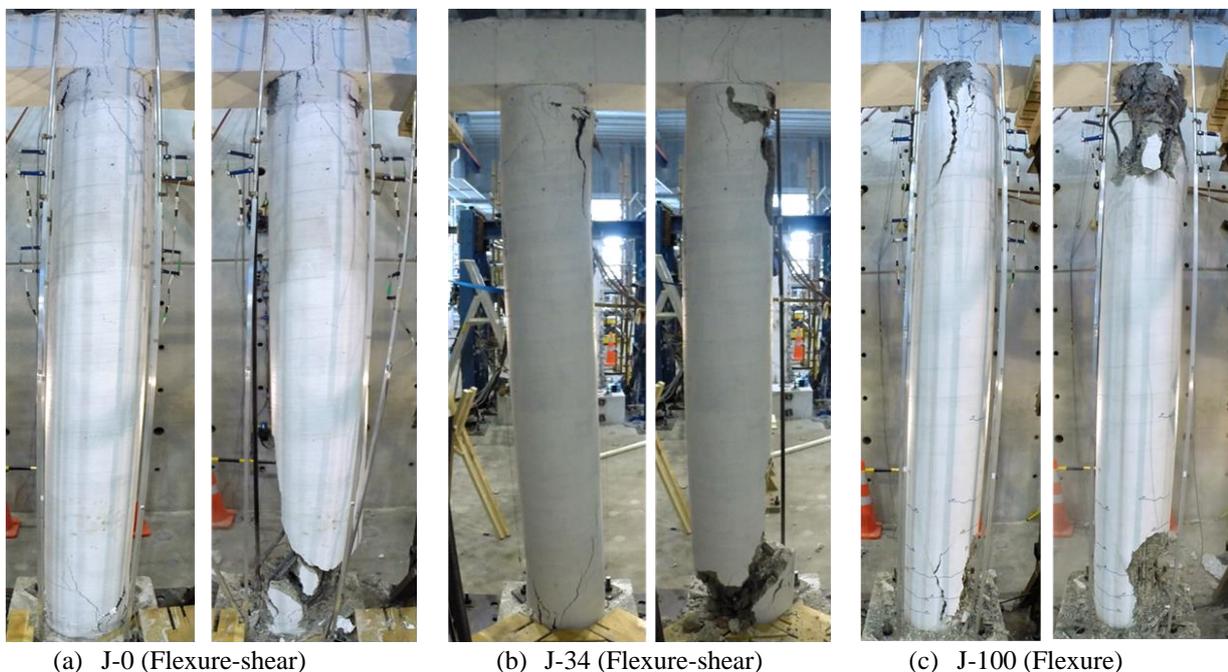


Figure 3. Damage state of subassemblies at the end of the experiment [17]

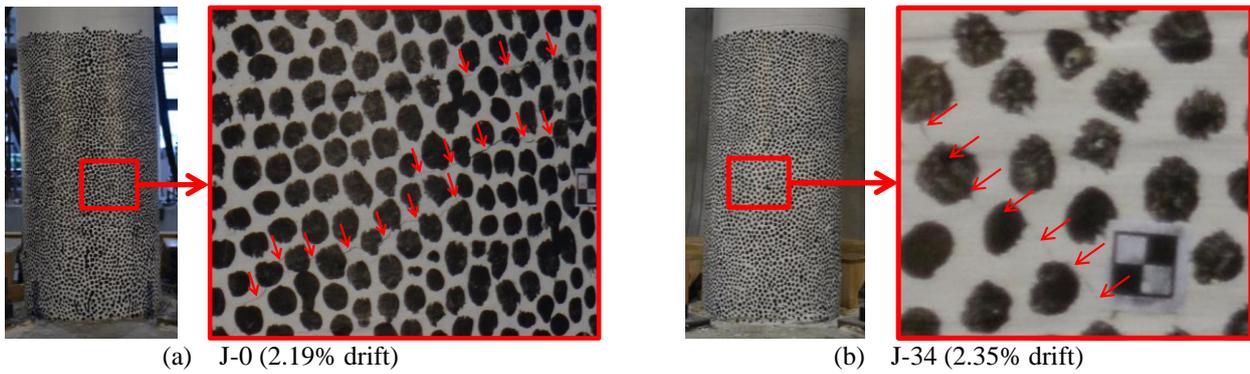


Figure 4. Formation of diagonal failure plane in J-0 and J-34 [17]

Sezen and Moehle [18] had identified the transition point between a flexure-shear and flexure failure mode as a shear capacity ratio of 0.7. The shear capacity ratio is defined as the ratio of flexural strength ( $V_p$ ) to the un-degraded shear strength computed using the Sezen and Moehle shear model ( $V_o$ ). The columns of the subassemblies, tested by Motter et al. [17], are compression-controlled; hence, the flexural capacity, likewise the shear capacity ratio, of the columns is highly dependent on concrete strength. As shown in Figure 5b, according to the Sezen and Moehle model, a slight variation in the measured mean concrete strength can cause a failure mode switch.

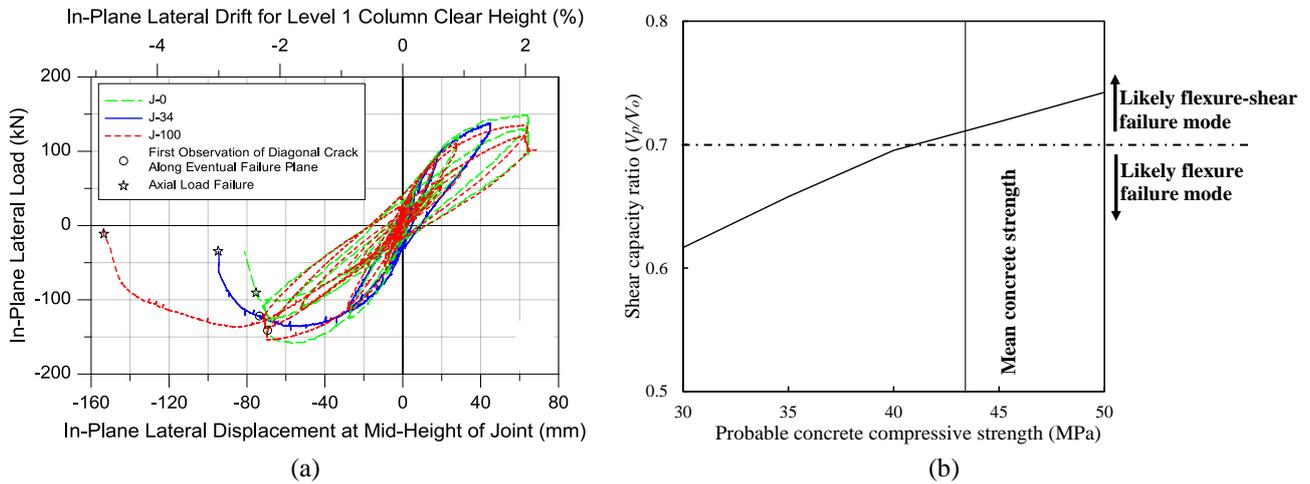


Figure 5. (a) Lateral load-displacement response of subassemblies. (b) Variability in shear capacity ratio due to variability in concrete strength [17]

## TRANSITION ZONE

All the RC columns described in the previous section experiencing failure mode variability between flexure-shear and flexure failure modes have shear capacity ratio between 0.65 and 0.72. The failure mode switch can be attributed to the proximity of the column shear capacity ratio to the Sezen and Moehle transition point of 0.7. The range of this proximity, i.e. lower bound and upper bound, is referred to as the transition zone. The definition of this transition zone is necessary to identify columns susceptible to failure mode variability. Columns outside the flexure – flexure-shear transition zone have a lower likelihood of experiencing a switch between these two failure modes.

With an aim of further understanding the transitions between failure modes, the ACI 369 rectangular column database [19] was examined. Figure 6 shows the distribution of reported failure mode for the column specimens with respect to shear capacity ratio and aspect ratio ( $a/d$ ). For columns with aspect ratio greater than 3, the zone where both flexure and flexure-shear failure modes are reported is between shear capacity ratio of 0.6 and 0.8. The distribution of the reported three failure modes in the column database is presented in Figure 7a. According to the three-group classification, there is a probability of 0.5 that a column with a shear capacity ratio of 0.7 will be flexure-governed or flexure-shear governed. This corroborates the value of 0.7 provided by Sezen and Moehle [18] as the transition point from a flexure to a shear critical zone. It is noteworthy that a transition zone exists between the shear and flexure-shear failure modes as well; however, there are some similarities in damage mechanism between these two failure modes once a diagonal failure plane is formed, hence step-change in behavior may not be expected. For the purpose of this study, the shear and flexure-shear failure modes can be combined together so as to have a binary classification – likelihood of developing a diagonal failure plane (Figure 7b).

According to Figure 7b, experimental data suggest that the likelihood of developing a diagonal failure plane is 0.5 at shear capacity ratio equal 0.7.

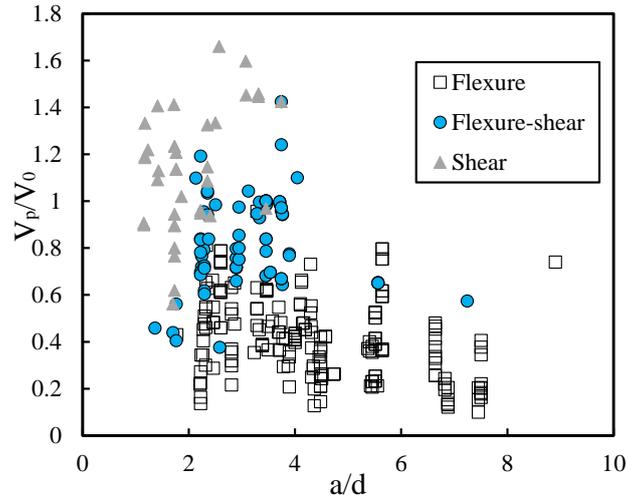


Figure 6. Reported failure modes for RC columns in the ACI 369 database as a function of shear capacity ratio and aspect ratio

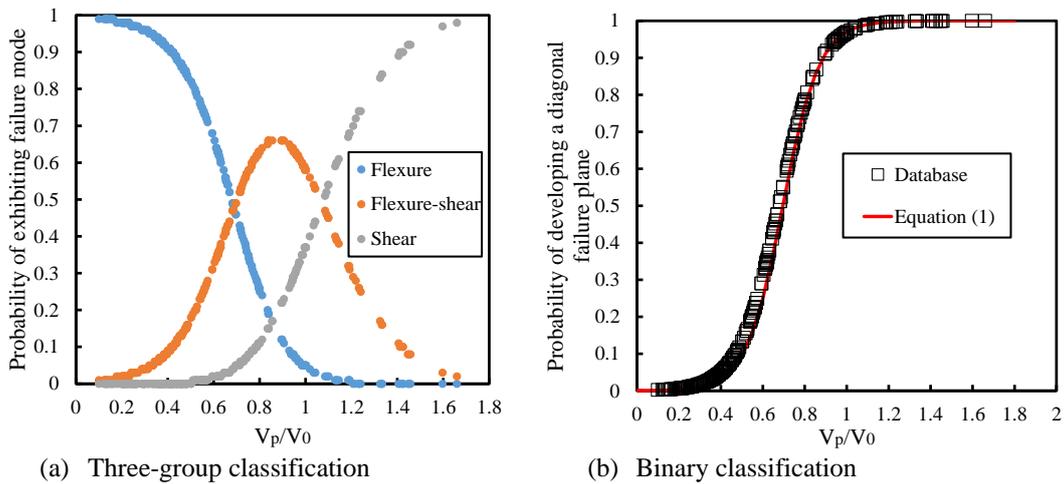


Figure 7. Distribution of RC columns in the ACI 369 database as function of shear capacity ratio

An equation which fits the curve in Figure 7b can be expressed as:

$$P(DFP) = \frac{e^{-8+11.5\frac{V_p}{V_0}}}{1 + e^{-8+11.5\frac{V_p}{V_0}}} \quad (1)$$

Where  $P(DFP)$  refers the probability of developing a diagonal failure plane.

Equation (1) can be adopted in a probabilistic framework to estimate the likelihood of developing a diagonal failure plane. Figure 8 examines reported failure modes and predicted probabilities, using Equation (1), for columns with shear capacity ratio between 0.6 and 0.8. A significant proportion of columns reported as flexure-critical have shear capacity ratio greater than 0.7. Equation (1) predicted a likelihood of being flexure-critical between 0.2 and 0.4 in those cases. A similar situation is noticeable for columns, having shear capacity ratio lower than 0.7, reported as being shear-critical. Based on this, the shear capacity ratio region between 0.6 and 0.8 is referred to as the failure mode transition zone. Columns within this zone can exhibit a flexure failure mode or a flexure-shear mechanism, and the possibility of failure mode switch must be accounted for.

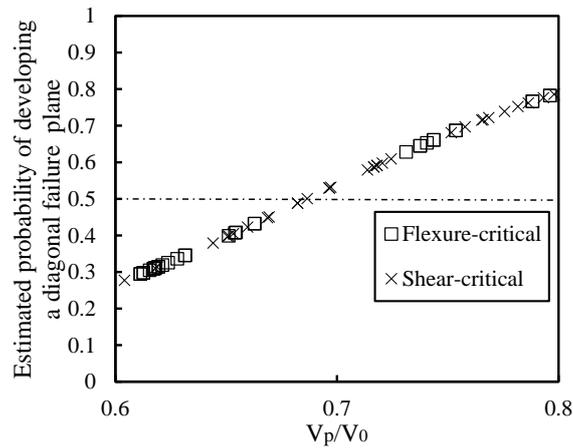


Figure 8. Estimated probability of developing a diagonal failure plane for columns with shear capacity ratio between 0.6 and 0.8

### ACCOUNTING FOR INFLUENCE OF FAILURE MODE IN SEISMIC ASSESSMENT

Experimental data have shown that the seismic response of RC components are failure mode dependent. Even for nominally identical RC columns, there is a significant step change in the behavior if a diagonal failure plane forms. Accounting for the dependence of deformation capacity on failure mode, ASCE/SEI 41-13 [20] incorporates this step change in the provision of acceptance criteria for RC columns by requiring the engineer to first establish the likely failure mode and then determine the appropriate deformation capacity. Also, in order to account for uncertainty in the prediction of failure mode for components within the failure mode transition zone, ASCE/SEI 41-13 provides a conservative upper bound shear capacity ratio of 0.6 for classifying a column as flexure-critical. Current seismic assessment provisions, such as ASCE/SEI 41-17 [3], however, provide empirical models that do not directly account for the influence of failure mode on seismic response. It is understandable that acceptance criteria in these provisions are meant to provide conservative deterministic estimates of probable drift capacities. However, in order to provide a realistic assessment of structures, there is a need to develop tools that account for the influence of failure mode and its uncertainties on probable component capacity and global response.

ASCE/SEI 41-17 [3] provides a linear equation for estimation of plastic rotation capacity of RC columns as a function of transverse reinforcement ratio, axial load ratio and shear capacity ratio. Although the shear capacity ratio is a failure mode index, unlike ASCE/SEI 41-13, the linear equation in ASCE/SEI 41-17 blurs the boundary between failure modes; thereby ignoring the step change in behavior which may occur if a diagonal failure plane develops (Figure 9a). While studies [21] have shown that the provisions in ASCE/SEI 41-17 provide a median estimate across the column database used in the development of the capacity equations, the significance of damage mechanism on the component level to global response of RC structures warrants the need to ensure that adequate consideration of failure modes are incorporated as part of a reliable seismic assessment framework.

In a probabilistic framework, treatment of failure mode uncertainties for components in the failure mode transition zone may be deemed necessary. Outside of this zone, this may not be required as the likelihood of a failure mode switch would be insignificant (Figure 9b). As shown in this figure, the failure mode can be identified using a failure mode index. While this paper has focused on the shear capacity ratio as the failure mode index, due to its adoption by the ASCE/SEI Standard, other failure mode indices (e.g. Zhu et al [22]) exist and can also be used if deemed more effective. The treatment of failure mode uncertainties will help incorporate the influence of probable failure mode on drift capacities at loss of lateral strength and drift at loss of axial capacity.

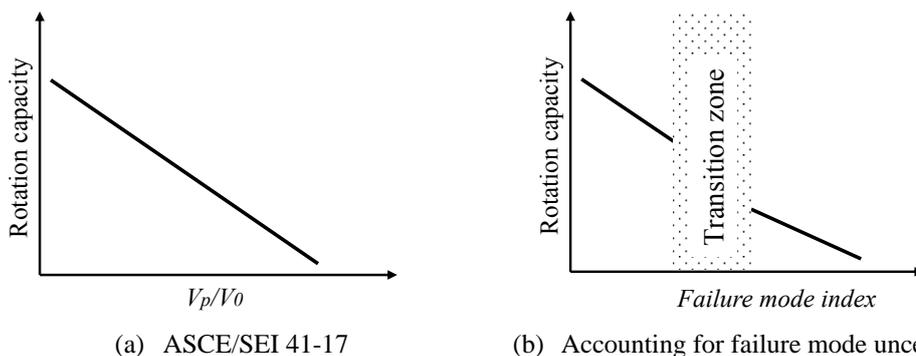


Figure 9: Accounting for influence of failure mode on deformation capacity in ASCE/SEI 41-17 and proposed procedure

## SUMMARY AND ONGOING STUDIES

Experimental tests provide evidence of the existence of a failure mode transition zone in which columns can exhibit failure mode variability. Due to strain rate, displacement history and/or material uncertainty, columns may exhibit an unexpected damage mechanism. Experimental tests have shown that columns that exhibit a flexure failure mode have higher ductility at onset of axial failure than nominally identical columns that exhibit flexure-shear failure mode. Based on these evidences, it is important to ensure that seismic assessment procedures account for the likelihood of a failure mode switch. The likelihood of a column experiencing a failure mode switch is dependent on the shear capacity ratio. Columns with shear capacity ratio between 0.6 and 0.8 may be susceptible to significant uncertainty in failure mode and subsequently, deformation capacity.

Procedures for seismic assessment and identification of collapse-prone reinforced concrete buildings must effectively capture and identify the probable damage mechanism of components and the resulting redistribution of loads. Open research questions on uncertainties in failure modes of RC components include:

**Treatment of failure mode uncertainty and its effect on fragility estimates of RC columns in probabilistic seismic assessment frameworks:** Conventionally, fragility functions, defining the probability of exceeding a limit state, developed using models calibrated to experimental data, account for epistemic uncertainties in their development. It is essential to develop a methodology for treatment and incorporation of failure mode uncertainty in a probabilistic seismic assessment framework. This methodology should also enable proper combination of failure mode uncertainty with other sources of uncertainties. Such a methodology will help quantify the effect of failure mode uncertainty on fragility estimates on a component level.

**Effect of uncertainty in failure mode of components on global seismic performance:** Studies, such as Liel et al. [4], have shown the influence of modelling uncertainties on the collapse risk of RC structures by considering uncertainty in structural modelling parameters. According to the authors, incorporating modeling uncertainties results to a shift in the collapse fragility median and increase in dispersion. Numerical studies, aimed at understanding the effect of incorporating uncertainty in failure mode of RC components and subassemblies in numerical analyses, need to be carried out to further improve the state-of-the-art knowledge of collapse risk of older-type RC buildings.

The authors are currently conducting various studies to provide answers to these research questions.

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