Analysis of Deficient Reinforced Concrete Beam-Column Connections using Scissors Model

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Abstract: Macro-modeling techniques have been proved as suitable solutions for analysis and assessment of deficient reinforced concrete (RC) beam column joints subjected to seismic loads. The techniques vary from single rotational spring at the joint panel to multi-spring complex joint elements for individual response prediction at the panel and interface. The technique is used to bridge the gap between the rigid joint modeling leading to compromised structural safety and economy and finite element methods (FEM) resulting in very high computational effort. Joints built prior to development of seismic specifications exhibit certain deficiencies characterized by improper construction, weak materials, lack of transverse reinforcement, and lower reinforcement ratios. Deficient joints exhibit a brittle behavior when exposed to lateral loads.

Key Words: —*Beam-column joints, Panel Shear, Pinching, and Reinforced Concrete.*

I. Introduction

Development of optimized joint modeling approaches to simulate joint shear response is an active research field. Significant research has been conducted on the topic and numerous modeling approaches have been proposed in the last few decades. Literature reveals that the main mechanisms governing RC joint response are panel shear deformation and interface bond slip mechanism [1]. There is a delicate balance between accuracy and computational efficiency, one cannot be enhanced without compromising the other.

II. Review Of Existing Joint Models

The RC joint modeling techniques evolved over time from simple lumped plasticity models to Advanced Finite Element (FE) numerical simulations. In this study only lumped plasticity rotational spring and multi-spring models having high computational efficiency are discussed. The most common lumped plasticity rotational spring and multi-spring models are Alath and Kunnath [2] model with a single rotational spring at the panel, Biddah & Ghobarah [3] model, Lowes et al. [4] model, Mitra & Lowes [5] model, and Ning et al. [6] model with separate zero-length non-linear springs to capture individual responses both at the panel and joint interface as shown in Figure1. The other more recent multi-spring models include Grande et al. [7] Model and Shin and LaFave [8] Model considering individual responses with optimized mechanics.

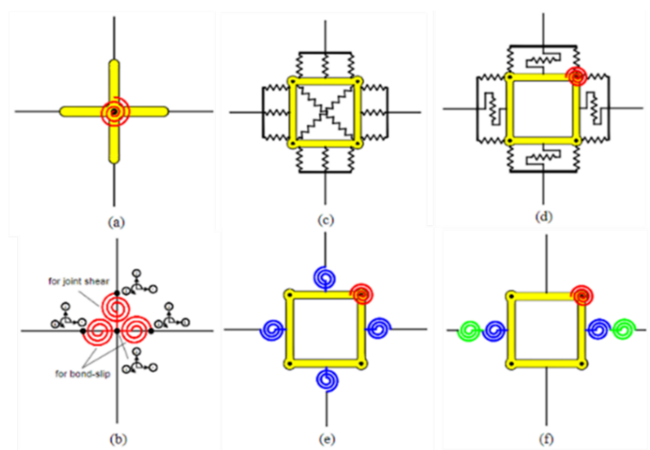

Fig.1. Rotation and Multi-Spring Models for macro level joint analysis [10]

Otani [9] and Anderson and Townsend [10] initiated the idea of introducing discrete inelastic action to analyze the non-linear behavior of joints in RC frames. Attempts were made to capture the non-linear flexural response of RC joints through a single plastic hinge at joint locations. The interface

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shear and bond-slip mechanisms were not accounted for in these models.

To characterize joint kinematics, Alath and Kunnath [2] used rigid offsets for the joint's flexural rigidity and its finite size. A rotational spring with deteriorating hysteresis loop was used to simulate joint panel shear deformation as shown in Figure 1. The individual rotations of connecting elements were represented by their respective constitutive models and hysteresis rules. The joint model does not account directly for the interface shear and bond-slip mechanism, whereas it is compensated for in most of the constative model parameters as discussed in the following sections.

III. Modeling In Numerical Framework

OpenSees finite element software was used for numerical simulations based on its outstanding macro-modeling capabilities. For modeling the concrete material "Concrete 04 - Popovic's" model was adapted. while "Steel 02 - Giuffr'e-Menegotto-Pinto" model was used for reinforcing steel. Deformation based fiber sections were used to model connecting beams and columns. In case of code compliant models, the STKO automated computational scheme for confined concrete was utilized. For non-compliant specimen the cover and core concrete were kept the same.

On the other hand, the "Pinching 4 Uniaxial Material" model, which necessitates the definition of multi-linear M-Ѳ curve, was used to simulate the non-linear response of the zero-length rotational spring. The cyclic behavior of the spring using pinching4 material model is governed by several calibration parameters. These calibration parameters control the pinching, stiffness degradation, strength degradation, and energy degradation. The parameter description behavior visualization is given in Figure 2.

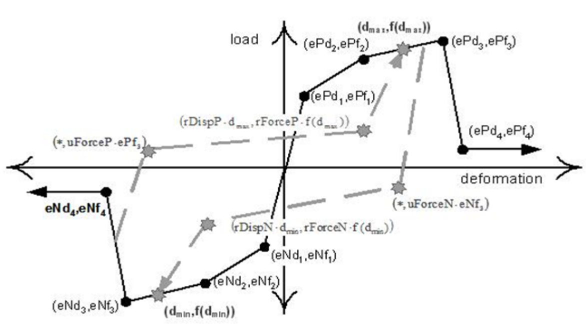

Fig.2. Uniaxial Material- Pinching4 Model with visualization of floating-point values [7].

IV. Constitutive Models

The shear behaviour of spring is defined by five main phases as depicted in terms of M-Ѳ relationship in Figure 3.

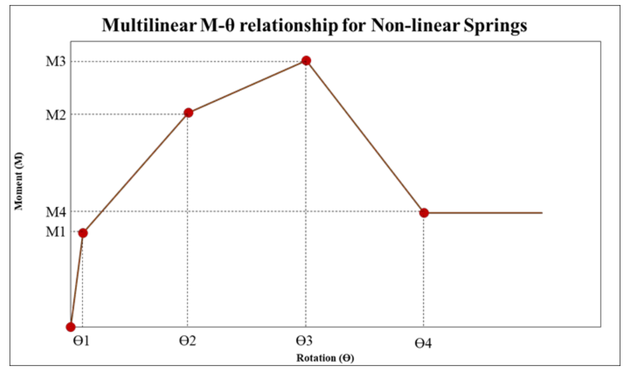

Fig.3. Multilinear constitutive behaviour defining joint response

The cracking shear stress 'τ1' value employed in this study is proposal by Uzumeri [11].

$$\tau_1 = 0.92\sqrt{f_c}\sqrt{1 + 0.29\sigma_j} \qquad (1)$$

Where f_c' (MPa) is the concrete's compressive strength and σ_j (MPa) is the column's axial stress ($N/b_c h_c$).

Literature provides many methods to estimate maximum response in shear 'τ_{max}'.

- Kim and LaFave [12]
- Jeon [13]

Kim and LaFave [12]

The model considers the key parameters given in equation (2) which affect the joint shear response.

$$\tau_{max} = 0.483\,(BI)^{0.3}(f'_c)^{0.75} \quad (MPa) \qquad (2)$$

Jeon [13]

This model considers the same variables proposed by Kim and LaFave [16] in different correlations.

$$\tau_{max} = 0.409(BI)^{0.495}(f'_c)^{0.941} \quad (MPa) \qquad (3)$$

Other models that are available in the literature for the remaining two shear stress values (i.e., τ2 and τ4), as well as the four shear strain values. Among them the following constitutive models are considered in current study:

Celik and Ellingwood [14]

The floating-point values of pre and post peak shear stress, τ_2 and τ_4 are presented as a fraction of peak shear stress τ_3.

Table.1. Shear stress parameters for joint panel rotational spring

Model Parameters	Rotational Spring Shear Stress Properties					Rotational Spring Shear Strain Properties			
	τ_1	τ_2	$\tau_{3\,(\tau max)}$		τ_4	Υ_1	Υ_2	Υ_3	Υ_4
	Mpa	Celik	Kim	Jeon	Celik	Celik	Celik	Celik	Celik
MODEL EJ-1A	1.366	2.284	2.267	2.409	0.913	0.0001	0.002	0.0001	0.03
MODEL EJ-2A	1.366	2.284	2.032	2.011	0.913	0.0001	0.002	0.0001	0.03

Table.2I. Joint Moment parameters for panel rotational spring

Model Parameters	Rotational Spring Moment Properties				
	M_j (τ_1)	M_j (τ_2)	M_j ($\tau_{3,\,\tau max}$)		M_j (τ_4)
	N-mm	Celik	Kim	Jeon	Celik
MODEL EJ-1A	8.50E+07	1.40E+08	1.40E+08	1.50E+08	5.70E+07
MODEL EJ-2A	8.70E+07	1.50E+08	1.30E+08	1.30E+08	5.80E+07

V. Results And Discussions

The numerical results are recorded in terms of observed experimental response parameters and are plotted in comparison to the experimental results. The recorded response is presented in terms of backbone curves, hysteretic loops, and cyclic Stiffness degradation.

For plotting the load vs drift curves, the drift is calculated from the ratio of beam vertical displacement and length of the beam. The scatter in results was calculated by comparing the ultimate numerical force $F_{i,num}$ reached and corresponding ultimate values obtained from experimental $F_{i,exp}$ backbone curves.

$$Mean\ Percentage\ Error = \frac{|F_{i,exp} - F_{i,num}|}{F_{i,exp}} x100 \tag{7}$$

To observe the cyclic stiffness degradation, the ratio of peak force (KN) in each cycle and corresponding displacement are plotted against the percent drift.

As the Scissors model considers only the panel plasticity, the results are expected to be overestimated compared the true structural response. The behavior is justified as the main contributor to joint stiffness degradation is the interface damage. As the there is no plasticity or damage at the interface, no stiffness or strength deterioration occurs. The wholistic load effect is transferred to the panel, where the confinement effect from the column axial load minimizes the stiffness and strength deterioration.

4.1 Model EJ-1A

For compliant model (EJ-1A) the most suitable results were obtained from the combination of Shin1_Jeon. The remaining combinations of constitutive models exhibited overestimated response. Similar trends were followed by remaining constitutive models.

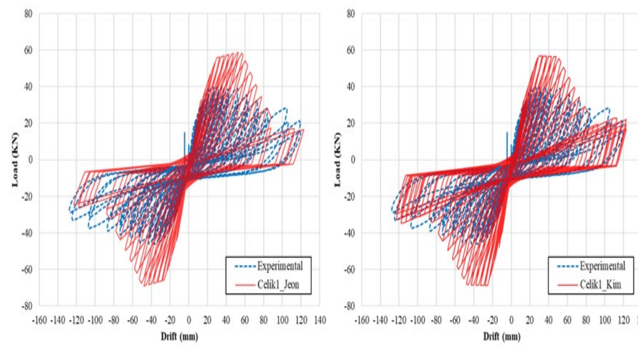

Fig.4. Hysteretic loops for model EJ-1A obtained from Scissors joint element

The backbone curves obtained through numerical simulations are plotted in comparison to experimental as shown in Figure 5.

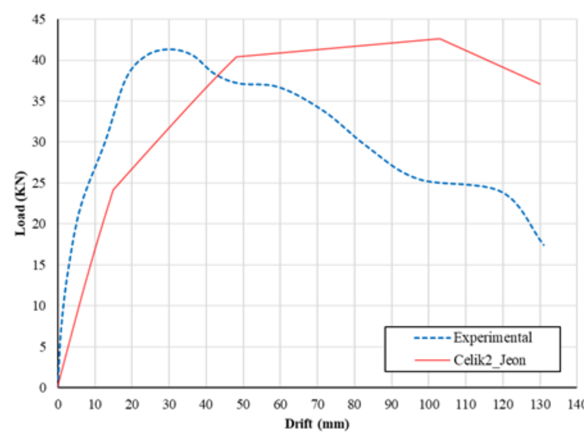

Fig.5. backbone curves for model EJ-1A obtained from Scissors joint element.

In case of Scissors model the initial stiffness is underestimated in almost all cases, while it is overestimated in later stages. As the plasticity is lumped at the joint panel with rigid boundaries, the entire demand is placed on a single rotational spring.

4.2 Model EJ-2A

EJ-2A, a non-compliant model with maximum deficiencies representing worst case scenario, exhibited highly overestimated response with all combination of constitutive models considered in this study as shown in Figure 6.

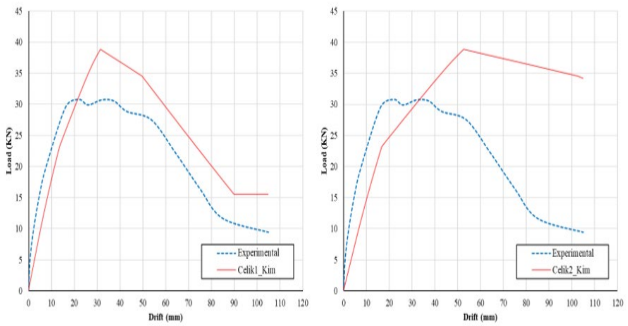

Fig.6. backbone curves for model EJ-2A obtained from Scissors joint element.

In case of EJ-2A the initial stiffness is also underestimated in almost all cases by Scissors model, while it is overestimated in later stages as shown in Figure 7.

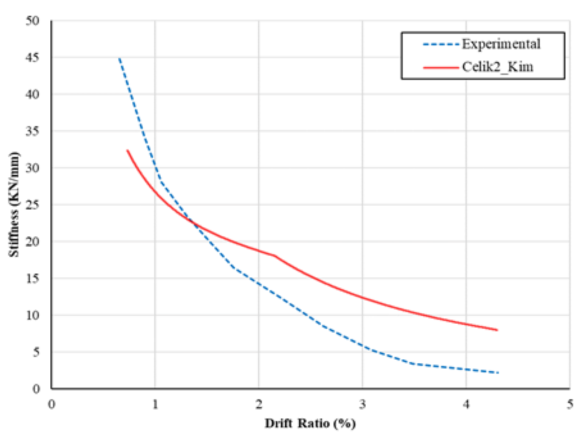

Fig.7. Stiffness degradation for model EJ-2A obtained from Scissors joint element

The mean percentage error in results was computed by comparing the ultimate numerical force Fi, num reached and corresponding ultimate values obtained from experimental Fi,exp backbone curves. The scissors model gives an overestimation of peak response for both code compliant (EJ-1A) and non-compliant (EJ-2A). The percentage error for non-compliant models is significantly higher than compliant models as obvious from Table 3. That is because the interface contributes significantly to energy dissipation through deformations and cracking, which in Scissors model is kept elastic and is not allowed to deform plastically.

Table.3. Mean percentage error observed in the study joint elements

Models	Error (%)
EJ-1A	17.44365151
EJ-2A	35.75647064

VI. CONCLUSION

In Scissors Model, the effects of bar-slip and interface shear are not considered separately.

- The model gives over-estimation of load-deformation response in almost all the cases except in case of Celik1_Jeon. The concrete cracking load is close to experimental however, the peak and post peak loads are overestimated.
- The numerical simulation and subsequent validation with experimental results during this study shows that the reliability of the model for shear response prediction of deficient RC is debatable.

The reliability of the model should be tested on a broader experimental database

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