Structural Modelling and Assessment of RC Beam-Column Joints Subjected to Seismic Loads for Progressive Collapse Approach

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Keywords: RC Beam-Column Joints, Progressive Collapse, Reinforced Concrete Finite Element Analysis, Structural Modelling

Abstract: The surrounding elements of a reinforced concrete frame generally undergo a significant overload that may result in their own collapse when the frame is subjected to progressive collapse as a result of the loss of a structural column. This may cause the frame to collapse. One of the most important factors in establishing the structural resiliency is the rotational capacity of the beams and, as a result of this, the beam-column connections. The response of the beam-column junction needs to be accounted for in any numerical models that are developed to analyse the response of the structure in the event of a progressive collapse. In this research, a systematic literature review of the different modelling approaches for beam-column joints, as well as the different constitutive models and how easy it is to implement them numerically, are presented. Some of these models are used to simulate the reaction of a reinforced concrete frame that has already been put through its paces. The structural response parameters that were calculated are compared to the experimental findings, and a discussion is had regarding the accuracy of each constitutive model.

1 INTRODUCTION

The term "progressive collapse" refers to a localized structural failure that causes the neighbouring members to fail, thereby setting off a domino effect. It can also be referred to as "disproportionate collapse." The progressive collapse of a structure can be caused by a wide variety of events, including but not limited to earthquake, localized fires, natural catastrophes, vehicle impacts, terrorist attacks, and many others (Yap and Li, 2011; Salgado and Guner, 2017).

In order to lessen the severity of the effects of a progressive collapse, a structure needs to incorporate a variety of different load routes (Lew *et al.*, 2014). In a prototypical instance of progressive collapse, wherein a structural column is absent, three significant load-resisting mechanisms emerge: The three mechanisms that contribute to the flexural resistance of structures under load are the compressive arch action, the plastic hinge action, and

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Propika, J., Septiarsilia, Y., Fitria, D., Susanti, E., Pertiwi, D., Istiono, H. and Komara, I.
Structural Modelling and Assessment of RC Beam-Column Joints Subjected to Seismic Loads for Progressive Collapse Approach.
DOI: 10.5220/0012105800003680
In *Proceedings of the 4th International Conference on Advanced Engineering and Technology (ICATECH 2023)*, pages 316-323
ISBN: 978-989-758-663-7; ISSN: 2975-948X

the catenary action. The compressive arch action is a result of the axial restraint of the surrounding structure, which provides additional flexural resistance. The plastic hinge action occurs when the formation of a plastic hinge causes large structural displacements on the beams. Finally, the catenary action is characterized by the development of tensile resistance due to the presence of cracks (see Figure 1).

Previous research has indicated that the ability of beams to rotate can effectively regulate the emergence of catenary actions. This phenomenon is attributed to the localized deformations that occur at the connections between the concrete beams and columns (Parastesh, Hajirasouliha and Ramezani, 2014). Furthermore, beam-column joints are essential for the purposes of resisting and distributing loads (Elsouri and Harajli, 2013), in addition to determining the rotational capability of the beams.

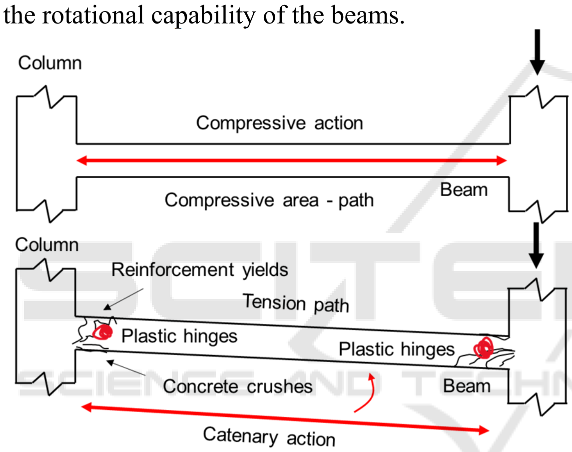

Figure 1: Plastic hinge mechanism (Lew *et al.*, 2014).

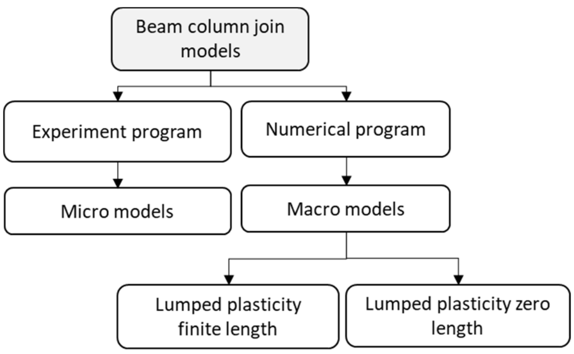

Figure 2: Illustrative common models to classify assessment analysis of RC joints.

In this study, both existing state-of-the-art numerical beam-column joint modelling methodologies as well as constitutive behaviors taken from the existing body of literature are analyzed and compared. The creation of novel modelling approaches that are both optimized for effectiveness and capable of duplicating the behavior of RC joints is a topic that is now the focus of academic investigation. In the most recent few decades, a considerable amount of research has been carried out on the topic, and a wide variety of modelling strategies have been proposed (Azoti *et al.*, 2013; Elsouri and Harajli, 2013; Lew *et al.*, 2014; Parastesh, Hajirasouliha and Ramezani, 2014; Khan, Basit and Ahmad, 2021). In general, existing beam column joint models can be divided into two categories: mathematical models and experimental models, as shown in Figure 2.

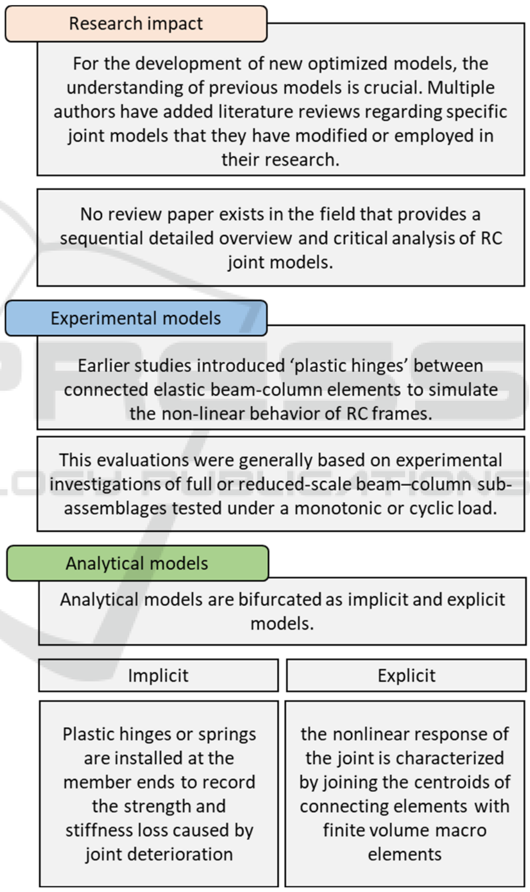

Figure 3: Scope of investigation; research impact – experimental models and analytical models.

This scope of the investigation also includes the research impact considering from various studies, including experimental program models and analytical models, as illustrated in Figure 3. This model criteria inputted on aspects of the collapse mechanism for RC structures (Lew *et al.*, 2014; De Risi *et al.*, 2016; Salgado and Guner, 2017).

Previous research developed a number of models that describe the cyclic behavior of beam–column connections and explain the gradual decrease in strength and stiffness that occurs over the course of multiple cycles (Parastesh, Hajirasouliha and Ramezani, 2014). In terms of the experimental program, these formulations were able to accurately represent the cyclic behavior of the beam–column couplings (Hosseini *et al.*, 2012). When several different formulations for the first quarter cycle are combined, the controlling equation that results are as follows:

$$\frac{M}{M_y} = 0.172 + 1.03\gamma - 0.167\gamma^2 - 0.00846\gamma^3 \quad (1)$$

where γ is the value that represent the stiffness when the hinge rotation and the derivative of *M/My* gives joint stiffness.

2 SIMULATION AND NUMERICAL MODELLING OF BEAM COLUMN JOINTS

Panel shear and bond-slip actions are the two primary variables that influence the behaviour of the beam-column joint. When extreme loading is applied to members that are adjacent to a beam-column junction, the joint panel zone experiences significant shear deformation as a consequence of the loading. In addition, decreasing the flexural resistance of the beams is a frequent practice that involves terminating the longitudinal reinforcing rebar inside the joint (Ilyas *et al.*, 2022).

Because of this, the frame's strength and stiffness are reduced due to the joint damage mechanism that is caused by high shear and bond pressures. As a direct result of this, the frame has less strength and less stiffness (Celik and Ellingwood, 2008). The rigid-joint, rotational-hinge, and component models are the three modelling strategies that have seen the most widespread application among the many beam-column joint modelling strategies.

Because rigid-joint models simulate an entirely rigid connection between the beam and column elements, joint deterioration can be omitted in these models (Salgado and Guner, 2017). As a result, moments can be entirely transferred from one element to the other. The physical joint core is contained within the rigid element region, which, as a result of its more responsive nature, causes the joint injury to become more concentrated at the point of contact with the beam or column. Rigid joints yield results that are somewhat accurate when beam-column joint degradation is not the dominating structural behavior. When this is not the case, these models fail to take into account the actual deformations of the joint panels, which leads to an inaccurate calculation of strength and deformation (Pantazopoulou and Bonacci, 1994).

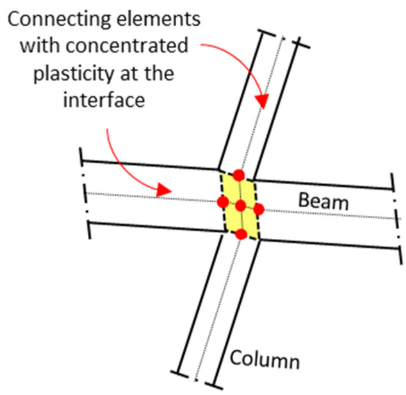

Figure 4: Simulation of Beam column joint modelling (Khan, Basit and Ahmad, 2021).

In the models of rotational hinge joints, there is a single rotational spring that is incorporated at the center of the beam-column connection. This rotational spring is responsible for the shear panel stress-strain displacement and nothing else. The connection is modelled with rigid-end offsets (Ilyas *et al.*, 2022). While the moment rotation constitutive behavior of the center spring is used to simulate joint deformations, the rigid links are used to ignore any damage that may have occurred in the components that make up the joint panel. This model was utilized quite frequently in the published works for example, (Celik and Ellingwood, 2008; Salgado and Guner, 2017; Khan, Basit and Ahmad, 2021), and despite the fact that its methodology was oversimplified, it produced findings that were reasonably accurate. However, when the bond-slip action is an essential behavior, you shouldn't use this model at all.

Component models incorporate a more realistic constitutive model, which specifically models joint panel shear deformation and bond-slip. This makes the component models more accurate representations of the underlying material. Continuous panel components or springs usually account for shear deformation, but 1-D springs account for bond-slip interactions. There have been many component models proposed in the scientific literature for example (Grande *et al.*, 2021; Khan, Basit and Ahmad, 2021; Ilyas *et al.*, 2022)); however, these models require many constitutive models for each considered behavior (such as a spring), which, in most cases, are not easily accessible or are difficult to obtain, which hinders their ability to be effectively applied in real-world situations.

2.1 Shear Panel

A calibrated joint-panel shear stress-strain response from experimental testing of specimens with a given shape and reinforcing configuration is used in most models (De Risi *et al.*, 2016). When using these models to perform an analysis of a structure that already exists or is in the planning stages, the accuracy of the calculations will be significantly impacted by the degree of similarity that exists between the structure being modelled and the experimental dataset that is being used in the model calibration (Ricci *et al.*, 2016). As a result, the currently available joint models ought to be utilized with extreme prudence.

Figure 5 shows that concrete cracking, stirrup yielding, shear strength, and residual joint shear capacity regulate joint panel shear stress-strain response (De Risi and Verderame, 2017). These four damage states serve as the backbone of the response (Celik and Ellingwood, 2008; Nawy, 2008; Alexander, Dehn and Moyo, 2015; De and Wallace, 2015).

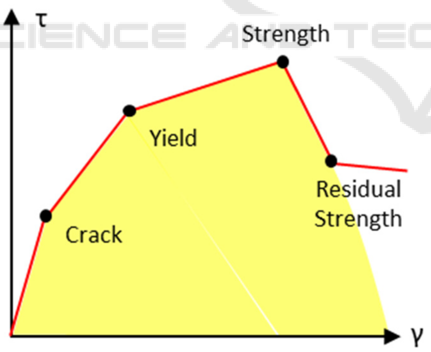

Figure 5: Shear panel damage conditions (Kim and Lafave, 2008).

The constitutive model developed by Teraoka and Fujii characterizes each damage state with a predetermined strain pattern that is derived from an experimental collection through curve fitting. The relationships were established purely on the basis of the properties of the concrete and the type of joint (i.e., an exterior or an interior joint, and transverse beams or not). As a direct result of this, the model allows for the rapid definition of four joint backbone locations. On the other hand, the reduced complexity may lead to a reduction in dependability and accuracy (Pacific Earthquake Engineering Research Center, 2000).

Another study proposed a constitutive joint backbone reaction model (De Risi *et al.*, 2016; Ricci *et al.*, 2016) and uses fixed strain values and percentages of the maximum shear stress. The theoretical shear capacity of the joint is calculated using the modified compression field theory (Kim and Lafave, 2008). However, the model uses an iterative, 17-step calculation process to determine the shear stress capacity, which limits the model's ability to be used in real-world situations. The fixed stiffness values for each segment used in the presented model (Filippou, Popov and Bertero, 1982), which are based on the joint maximum shear stress, are used to compute the stress and strain backbone points. Because it was calibrated for internal beam-column joint assemblies with inadequate transverse reinforcement, it may not be as accurate for joints with proper design.

Additionally, the joint-shear backbone can be defined using the variety model with only two points (Khan, Basit and Ahmad, 2021): brittle failure after the adjacent beam's flexural yield and maximal shear capacity. This model is at the beam-joint contact, not the beam-column connection. Model joint reaction limits beam moment capacity. The method is comparatively straightforward due to the bilinear constitutive behavior. However, this model, which employs fixed maximal strain and stiffness values, was created exclusively for interior joints. According to Kim and LaFave (Kim and Lafave, 2008, 2009), the damage states of crack, yield, and residual strength are inversely correlated with the highest shear and strain values. Its "unified" constitutive model, which does not use fixed values of stress or strain, is its primary benefit. It considers the concrete's compressive strength, in-plane and out-of-plane geometry, joint eccentricity, beam reinforcement, and joint transverse reinforcement to calculate maximum shear and strain.

2.2 Cyclic Model

The hysteresis response at beam-column joints under cyclic loading conditions is usually very pinched. The beam column joint still experiences unloading as a result of the compression-tension alternation between each mechanism, despite the fact that this study only conducts nonlinear static analyses. For analyses of progressive collapse, it is crucial to take the joint's hysteretic reaction into account. The combined cyclic behavior suggested by Khan et al. is depicted in Figure 6 (Khan, Basit and Ahmad, 2021).

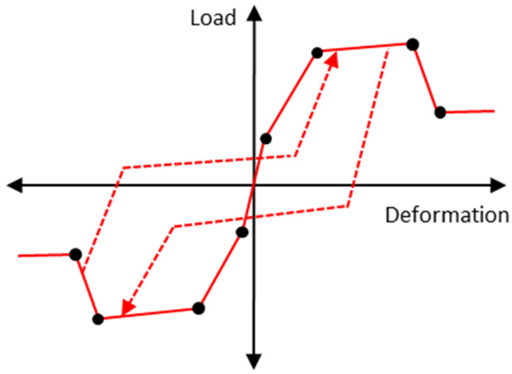

Figure 6: Hysteretic loop behaviour of beam column joint (Dabiri, Kaviani and Kheyroddin, 2020).

The majority of current studies determine the cyclic pinching parameters based on an experimental approach to curve fitting, much like the backbone response of the joint; very few studies suggest pinching that is generally applicable. Due to the study's understandable analysis of 124 beam-column joint specimens.

2.2.1 Rotational Hinge Models

The stress–strain envelope and cyclic hysteretic rules are standard input parameters in rotational hinge models. A multilinear monotonic curve with many constitutive models based on empirical equations and experimental observations controls these models. This curve controls these models. Several calibration parameters determine the pinching effect, strength, stiffness, and energy degradation in following cycles based on structural reaction. Structural response determines these characteristics. The original model in this field was based on the idea that the joint should flex plastically under lateral loads (Ilyas *et al.*, 2022). This concept served as the framework upon which the model was built. The non-linear response that was created by the shear demand that was made on the beam as a result of the flexural response of the connecting elements was able to be captured by the two rotational hinges that were placed at the extremities of the member. These hinges were able to do this because they were located at the extremities of the member.

In rotating hinge models, examples of typical input parameters are the stress–strain envelope and hysteretic rules that explain cyclic activity. Both of these types of rules describe cyclic behavior. A multilinear monotonic curve guides these models. Using empirical equations and actual measurements, different constitutive models define this curve's important points. This curve controls and directs the majority of these models. This curve is also the primary controller for these models, acting in that capacity here. Depending on the structural reaction, calibration factors regulate the pinching effect, strength, stiffness, and energy degradation in subsequent cycles. These parameters are determined by the actual structural response. The real structural response serves as the foundation for all of these factors. Ilyas et al., (Ilyas *et al.*, 2022) developed the first model in this field, and it was founded on the concept that the joint should be allowed to deform plastically when it is subjected to lateral loads. This idea was the foundation of the model. The non-linear response that was created by the shear demand that was placed on the beam as a result of the flexural response of the connecting parts was able to be captured by the member thanks to the placement of two rotational hinges that were positioned at the member's extremities. This can be seen on Equation (2-3).

$$K_{sp} = \frac{M_u - M_y}{\vartheta_{pl}} \quad (2)$$

$$z_c = \frac{M - M_y}{V} \quad (3)$$

Equation (1) states that each link has a bilinear elastic strain – hardening relationship-based M-curve. The equation provided effectively maintains the length of the plastic zone. The real-time value of the shear force is represented by the variable M. This approach is popular to be taken into design due to the easiest approach and its accuracy related to the joint mechanics. Notwithstanding, the design intent to fail on the part of simulate shear panel and diagonal cracks under cyclic loads. Further development to include shear panel and bar slip was studied by Ilyas et al., (Ilyas *et al.*, 2022) represented from various research with proposed (Celik and Ellingwood, 2008; Ricci *et al.*, 2016; Salgado and Guner, 2017; Grande *et al.*, 2021; Ilyas *et al.*, 2022) Equation (4) – (5) as follows:

$$A_{eff} = \frac{l_{emb}}{l_{db}} \times A_s \quad (4)$$

$$M_{pullout} = \frac{l_{emb}}{l_{db}} \times M_y \quad (5)$$

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE \quad (6)$$

Where l_{emb} is the embedment length while l_{db} is the development length and A_s is reinforcement area. D is illustrated as index of damage (0-1), δ_m is presented maximum deformation, δ_u is the ultimate deformation, β is the strength of deterioration rate, P_y is yield capacity and $\int dE$ represents hysteretic energy dissipation.

Figure 7: Fixed-end rotation considering deterioration in joint hysteretic behaviour (Ilyas *et al.*, 2022).

When considering the damage, (De Risi and Verderame, 2017) the model was developed to estimate the intensity of damage in relation to deformation and energy dissipation, as demonstrated in Equation (6).

The following case is flexural rigidity. Normally, the flexural rigidity is not considered into joints mechanics. The previous research learn and take into consideration the flexural rigidity of the joints, a model used rigid connections as illustrated in Figure 7 (Celik and Ellingwood, 2008; Ilyas *et al.*, 2022). The ability of these methods to forecast responses for a joint panel with a finite length is constrained. Joint mechanics did not take the joint's flexural stiffness into account. The corresponding constitutive models and hysteresis rules depicted the individual rotations of connecting elements. The cyclic hysteretic response was founded on experimental findings, whereas the shear stress-strain behavior was empirically derived. A rotational spring that simulates the shear behavior of the concrete core serves as the joint's sole non-linear reaction prediction device. Furthermore, the interface shear or bond-slip process cannot be predicted by this model.

A simplified rotational spring model was put forth by Khan et. al.(Khan, Basit and Ahmad, 2021) for the nonlinear cyclic response estimate of RC beam-column joints. As shown in Figure 8, the joint model was configured to have rigid offset components and focused plasticity. A shear-demand ratio was used to calibrate the rigid offsets, giving a reasonable approximation of the joint's initial stiffness. Each connecting member had two springs in sequence at the end. The non-linear reaction of the connecting element and joint was recorded by means of the two springs located at the end of each member. A distinct M- relationship was employed to ascertain the individual rotational springs. Each rotational spring exhibited a distinct moment-rotation reaction curve. The experimental findings of RC joints are very closely supported by the model-simulated response. The research did not include any corner or exterior joints, only internal joints where the confinement effects of the transverse beams are significant. The joint's bond mechanism was also not taken into consideration in the research.

Typically, the load-drift curve must exhibit a closure of approximately 20% and 5% as per the standard parameters established by FEMA356 and ASCE/SEI 41-06. Based on the studies examined by Khan et al. (Khan, Basit and Ahmad, 2021). The preliminary rigidity was observed to be closely approximated, exhibiting disparities of 20.3% and 5.4% for both FEMA356 and ASCE/SEI 41 – 06. The proposed beam design beam-column joint element with rigid offset and details of rotational springs, based on literature. On the basis of the available literature, the suggested beam design includes a beam-column joint element with a rigid offset and specifics of rotational springs (see Figure 7).

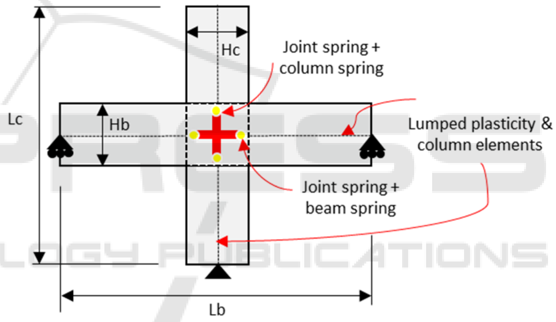

Figure 8: Experimental program – beam column joint element with rigid offset and proposed rotational springs (Khan, Basit and Ahmad, 2021).

The utilization of rotational hinge joint models allows for the autonomous evaluation of the non-elastic joint reaction while incurring only a negligible escalation in computational expenses. This approach offers a simpler and more dependable alternative to the traditional method of representing joints as rigid elastic components, while incurring only a marginal rise in computational expenses. On the other hand, this modeling technique makes it more difficult to achieve design objectives and achieve precise calibration in respect to a variety of loading scenarios and orientations. For the purpose of constructing an M-θ curve, it is necessary to make use of a significant amount of experimental data. In order to develop a model that is capable of simulating the joint response with a variety of design features, either a complicated calibration method that uses enormous data sets or numerous joint models that each have their own unique design details are required. Because experimental data of all potential orientations and loading scenarios are not currently accessible for calibration, the applications of these models are severely restricted. Utilizing the constitutive models that have been suggested by a variety of researchers in the past (Pantazopoulou and Bonacci, 1994; Celik and Ellingwood, 2008; Ricci *et al.*, 2016; De Risi and Verderame, 2017; Salgado and Guner, 2017; Khan, Basit and Ahmad, 2021; Ilyas *et al.*, 2022), will allow for the development of the M-θ curves. The constitutive models found in the scientific literature are expressed in terms of shear stress and strain, both of which can be transformed to M via joint mechanics.

The proposed cracking onset studied by Uzumeri, shear stress (τ_1) under Equation (7), while its maximum shear stress value (τ_{max}) represented from various studies as inform as follow Equation (8) – (11).

$$\tau_1 = 0.92\sqrt{fc}\,\sqrt{1 + 0.29\sigma_j} \quad (7)$$

$$\tau_{max} = 0.483(BI)^{0.3}(fc)^{0.75} \quad (8)$$

$$BI = \frac{A_{s,b}f_{y,b}}{b_b \times h_b \times f_c} \quad (9)$$

$$\tau_{max} = 0.642\beta\left[1 + 0.555\left(1 - \frac{h_b}{h_c}\right)\right]\sqrt{fc} \quad (10)$$

$$\tau_{max} = 0.409(BI)^{0.495}(fc)^{0.941} \quad (11)$$

The Equation (8-9) is in accordance with Kim and LaFave, where Equation (10) follow the calculation of Vollumn and Newman. As the other illustrations, Jeon proposed Equation (11). The models that have been suggested by a variety of researchers can be used (Yap and Li, 2011; De Risi *et al.*, 2016; Ricci *et al.*, 2016; Salgado and Guner, 2017; Grande *et al.*, 2021; Khan, Basit and Ahmad, 2021) for the purposes of calculating the remaining values of pre-peak and post-peak shear stress and strains.

3 CONCLUSIONS

A level of understanding, analysis, and evaluation of the response of RC beam–column joints that has not been seen in previous decades has been attained thanks to the significant advancements achieved in these areas. The non-linear reaction of joints in RC frames that have been subjected to lateral loads has been modeled using a variety of different modeling approaches and methods. The non-linear response of RC joints is dominated by two primary mechanisms: panel shear deformation and the bar–slip mechanism. These mechanisms, which have been modeled using a variety of different approaches, are responsible for the majority of the non-linear response. In recent times, there has been a substantial development in the modeling techniques, which has resulted in an improvement in accuracy and a reduction in the amount of computational effort required. The early models were built on the results of experimental research; however, it was discovered that these models were unreliable because they were contingent on a large amount of experimental data. As our knowledge of how connections behaved expanded, more complex and accurate models were put forward to explain this behavior.

For the purpose of connecting the elastic beams and columns to the joint in rotational spring models, a central zero-length element is utilized as the connection point. Because the complete non-linear behavior is combined into a single rotational spring, it is challenging to individually evaluate the joint panel shear, interface shear, and bar–slip mechanism. This is because the non-linear behavior is encapsulated in a single rotational spring.

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