Journal of Engg. Research Vol. 8 No. (4) December 2020 pp. 63-79 https://doi.org/10.36909/jer.v8i4.8043

A review on reinforced concrete beam column joint: Codes, experimental studies, and modeling

Basem Abdelwahed*'**

**Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt*
Corresponding Author: bs_hadi@mans.edu.eg
***Free University of Brussels, Brussels, Belgium*
bsalahab@vub.ac.be

Submitted: 14/03/2019
Revised: 15/10/2019
Accepted: 20/10/2019

ABSTRACT

Reinforced concrete frames are commonly used systems in buildings. The philosophy behind the proper design for this type of frames is to provide them with sufficient ductility. The structural ductility of a frame is mainly determined by the ductility of its components, i.e., the beams, columns, and joints forming this frame. Beam-column joint role in a building is to connect its components together and enable these components to reach their ultimate resistance. Its stiffness, strength, and ductility are key characteristics needed to guarantee efficient building behaviour under the action of different loads. Previous research attributed some building's damage to inadequate reinforcement details of its joints. Deficiency in joints performance is related to inadequate codes guidelines or to bad construction practice. This paper reviewed the provisions of three different codes (ACI 318-08, Eurocode 8, and ECP-203) concerning the proper design and detailing of different joints. This review study aims to introduce a wider overview on the assessment of joints performance in buildings under different loading scenarios. This data base will enable practicing engineers to identify the joint key parameters with providing different analytical procedures. This study investigates joints in different configurations. These include planner joints, joints with transverse beams, and the common joint situation with the presence of both transverse beams and slab. This survey includes experimental and analytical representation of the previous mentioned joints. Different retrofitting schemes are presented as well for every considered joint. This review allows to identify the evolution of joints capacity in function of reinforcement detailing, level of axial stresses, and loading history. The analysis shows that a decrease in joint resistance can be recovered by using i) haunches brackets, ii) FRP, or iii) post tension metal strip.

Keywords: Beam-column joint; Code provisions; Frames; Joint efficiency; Retrofitting schemes.

INTRODUCTION

The proper reinforced concrete RC frame response under different load scenarios is based on the relevant design and good reinforcement detailing of its structural components (beams, columns, and joints (Park et al., 1975)). The RC frame beam-column joint BCJ is located in the column part at the beam intersection location (ACI 318-08). It is considered as an important connecting component to transfer loads among beams and columns. Stress concentrations are observed at BCJ location in RC frame buildings as a result of discontinuity in its geometry. This discontinuity hinders linear strain distribution in the joint region (Salah et al., 2017). Many failures are recorded at or near the joint location; the former is due to inadequacy in joint shear reinforcement, and the latter is attributed to lower flexural capacity of the adjacent elements to the joint (beams, columns). **Figure 1** presents the most probable failure modes of different BCJ types. **Figure 1** shows the forces and moments acting on knee, exterior, and interior joints as a result of horizontal load action. The figure shows beams and columns internal forces equilibrium inside the joint by forming both diagonal tensile and compressive forces. Proper joints are required to assure RC frame ductile behaviour by enabling the adjoining elements to reach their ultimate capacity (Long, 2013). Joints have different types based on the number of terminated columns and beams at its location (interior, exterior, and knee) as presented in **Figure 2** (ACI 318-08); each joint requires a specific reinforcement scheme based on its geometry as shown in **Figure 2**.

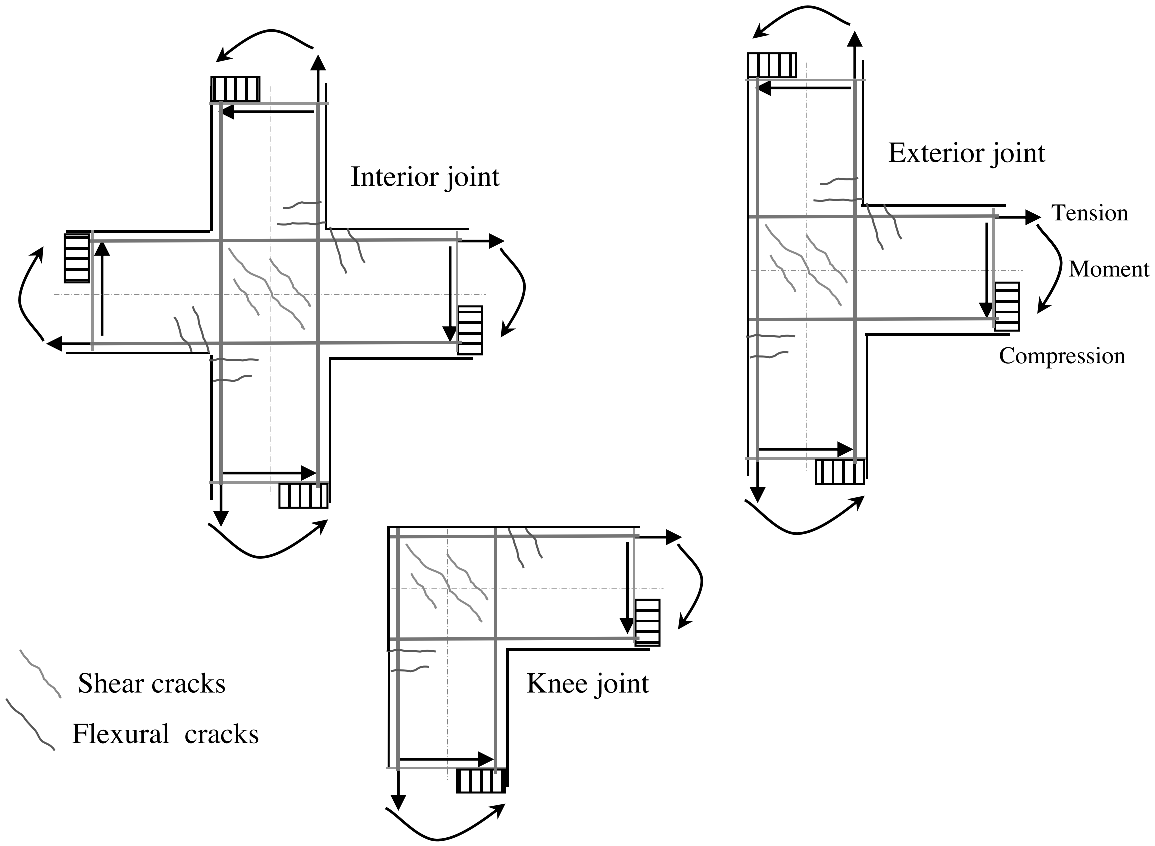


Fig. 1. Shear and flexural cracks expected in different BCJs (Yasser, 2012).

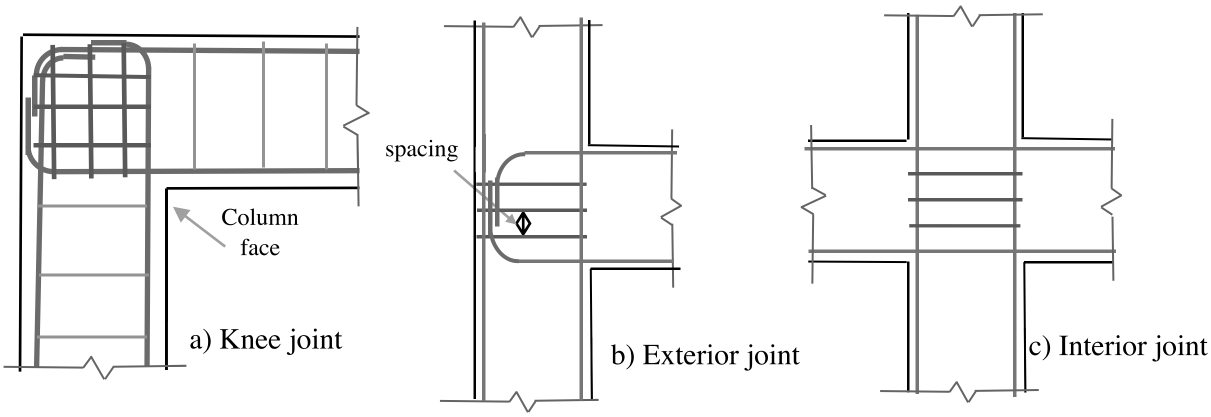


Fig. 2. Typical reinforcement details for different BCJs.

Hassan in 2011 collected some parameters that govern the joint performance such as anchorage type, reinforcement ratio, joint aspect ratio, joint confinement, and column axial stress level. Accordingly, he discussed distinguished experimental tests and different building failures observations, then attributed these joint failures to the following:

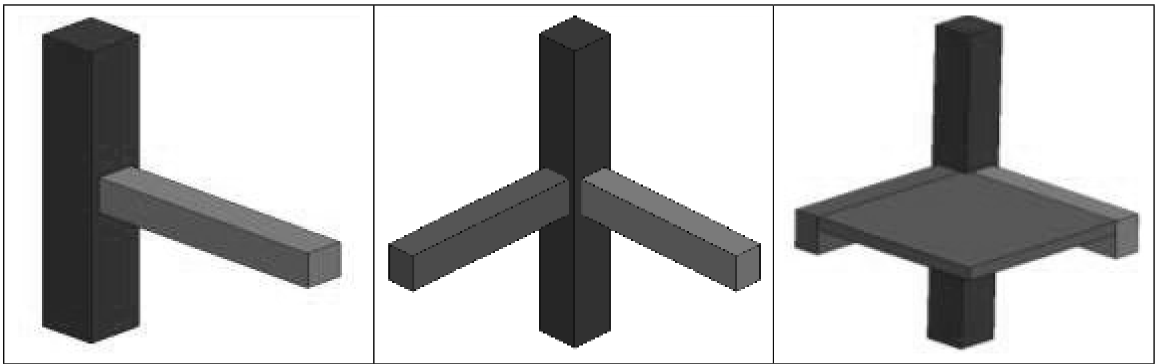
1. Anchorage failure at joint face due to inadequate development lengths;
2. Shear failure within the joint area;
3. Concrete crushing failure in compression due to high strut forces with insufficient confinement.

These joint failure modes limit joint efficiency and hinder reaching joints maximum strength. Also, he reported that these failure modes are more critical in an exterior and a corner connection than in interior joints.

Pantelides et al. in 2002 reported that, as a result of the action of multiple stresses on the joint panel zone (i.e., axial stresses from the column side and bond, bearing stresses from beam side), its behaviour is complex and motivates many research works to offer deeper understanding for it.

Efficient joint performance in terms of strength and ductility can be reached by relevant beam/ column element dimensioning with well-designed/detailed reinforcement as reported by Salah et al., 2017. Strong column weak beam principal is an important key parameter controlling structures performance. Isik et al. (2016) observed extended damage in structures with weak column-strong beam as such structures were frequently used for architectural reasons. As the damage level is dependent on beam to column strength ratio, they studied different sizing relationships between different joint's elements. They noticed sever damage in structures with less column/beam moment strength ratio. They presented different strengthening methods for columns in such buildings in order to mitigate building total collapse. Mondel et al. (2013) observed a direct relation of the column/beam strength ratio on the structure response factor. To avoid column hinging failure mode, Ye et al. (2008) recommended the consideration of floor slab in calculating beam stiffnesses. Mitesh et al. (2018) proposed the use of variable column/beam strength ratios along the building height to improve its collapse resistance. Strong column weak beam principle among the several joint design key parameters governs the joint stiffness degradation rate at early loading stages as Vafaei et al. (2019) noticed. Park et al. recommended lower reinforcement ratios for the adjacent beam and column to the joint to achieve higher efficiency levels. In order to control the propagation of the joint main diagonal cracks, Mac-Gregor et al. in 2003 specified a value of ft/fy as a limit for the beam and column reinforcement ratio, in which ft is the concrete tensile strength and fy is the reinforcement yield stress.

This study investigates part of the joints that appeared in different structures. These include planner joints, joints with transverse beams, and the common joint situation with the presence of transverse beams and slab as presented in **Figure 3**. This study offers a detailed survey of the design and detailing requirements of BCJs in a moment resisting RC frames, in parallel with the provisions of three different codes (ACI 318-08, Eurocode 8, 2004, and ECP-203, 2017).



a) planner joint	b) 3-D joint	c) 3-D joint with slab

Fig. 3. RC beam column joint in different buildings.

This survey includes experimental and analytical representation of the previous mentioned joints. Discussion on the role of different key parameters on such joints performance is presented. In BCJs, under different kinds of loadings (quasi-static and cyclic), the considered parameters are concrete compressive strength, fc; anchorage detailing (type and direction) of the beam main rebars; column axial stress level; joint aspect ratio; beam and column reinforcement ratio; joint shear reinforcement (amount and spacing) and lateral beam presence. With this survey, a wide range of research will be covered in order to give a brief guide to the practicing engineers. The current review deals with this topic through different aspects:

- Proper BCJ reinforcement detailing according to the considered three code regulations.
- Intensive survey on experimental studies dealing with many joint key parameters.
- Different numerical and analytical techniques used in joints simulation.
- Recent practical methods in joints upgrading.

We finally conclude with summary about the recent published studies followed by recommendations for the needed future work.

BCJs DETAILING

Different problems in reinforcement detailing inside the joint location can initiate and accelerate damage, for example, high bearing stresses on concrete inside the hooks with smaller radius or anchorage slippage failure of improper anchored bars. These problems can be avoided by satisfying the recommended hook bend radius mentioned by Salah et al. in 2017 and enabling full anchorage capacity of any embedded reinforcing bars inside the joint. The three considered codes have similar design philosophies concerning the primary dimensioning of different elements, recommended yielding mechanism, and the role of transverse reinforcement in confinement and shear resistance. On the other hand, minor differences are noticed in the location of joint critical section, column/beam strength ratio, area and spacing of joint transverse reinforcements, and the required longitudinal bar anchorage lengths.

In order to ensure proper RC frame behaviour under both vertical and different lateral loads, these codes propose regulations for reinforcement detailing requirements regarding joint confinement and proper anchorage condition for any longitudinal bars terminated inside the joint. These codes highlight the importance of providing adequate anchorage for the longitudinal bars and sufficient joint confinement. Terminated bars development length should be measured starting from the critical section; the critical section is at a distance of five times the bar diameter from column face or at the column face or after a concrete cover from the column face according to EC-8, ACI318-08, and ECP-203, respectively. After developing bars inside the joint, hook tail extension is needed to avoid bar pull out failure. The required length for that is 12, 10, and 12 times the bar diameter.

These codes (EC-8, ACI318-08, and ECP-203) specify additional detailing for shear reinforcement required to control cracking within the joint and bond deterioration of the main longitudinal reinforcement framing into the joint. The transverse shear reinforcement is needed to ensure truss mechanism, to confine the joint concrete, to improve concrete bond strength, to control cracking, and to increase joint ductility. The recommended stirrups amount varies according to the three codes. Both ACI318-08 and ECP-203 require transverse reinforcement in proportion to the strength of the concrete, whereas EC-8 determines the shear reinforcement based on the applied joint shear forces. Vertical stirrups horizontal spacing according to EC-8 is 150mm, which is more conservative than the ACI318-08 value. EC-8 additionally states that the horizontal confining reinforcement ratio in the joints at least should be equal to the specified ratio to columns critical locations, and at least one intermediate column bar should be provided at the joint on both sides. **Table 1** summarizes some differences between the considered codes.

Table 1. BCJ detailing according different codes.

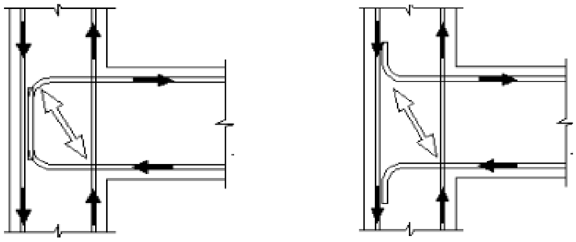
Item	ECP-203	EC-8	ACI318-08
Devlopment length	$l_d = (\alpha.\beta.\eta.f_y.d_b)/(4.f_{bu}.\gamma_s)$	$l_d = (\gamma_R.d_b.f_y)/(7.5 f_{ctm}.(1+0.8 f_a))$	$l_d = (d_b.f_y)/(5.4\sqrt{(f_c)})$
Critical section	Concrete cover after column face	$5d_b$ after column face	column face
Bar vertical tail	$12d_b$	$10d_b$	$12d_b$
Column/beam capacity	1.2	1.3	1.2
Stir. area	$A_{stir}=0.313.s.y_1.(f_{cu}/\gamma_c)/(f_{yst}/\gamma_s).(A_g/A_k -1)$	$A_{stir}/A_j.f_{yst}=2(V_{jh}/A_j)/(f_{ctd}+f_a/f_{ck}.f_{ctd}) -f_{ctd}$	$A_{stir}=0.3.s.h_c.f_{cu}.(A_g/A_k -1)$
Stir. spacing	150mm	min ($8d_b$, 175mm)	min ($h_c/4$, $6d_b$)

d_b is the nominal bar diameter, f_y is the steel yield strength, fc is the concrete compressive strength, f_{bu} is the concrete bond strength, and l_d is the bar development length, and more details about the used abbreviations are available in EC-8, ACI318-08, and ECP-203. The previous code regulations and provisions are mainly developed based on intensive experimental observations. A review on some of these experimental investigations is presented and discussed in the following section.

EXPERIMENTAL STUDIES ON BCJs

The joint stresses are critical because of the action of the above column axial compression force in combination with the high joint shear stresses at joint panel zone. This shear stress formation was attributed to column's bending moment direction change through the joint (Salah et al., 2017). The magnitude of the diagonal tensile stresses in the joint panel zone is found dependent on the beam main reinforcement ratio and the column axial stress level (Park et al., 1975). Many studies were focused on this critical point in the structures to gain more insight into that. Wight et al. in 1985 studied RC joints with different configurations; they concluded that, for efficient joints performance, the developed shear stress should not exceed 1, $1.25\sqrt{f_c}$ for the exterior and the interior joint, respectively. In addition, they concluded that joints with expected slippage failure have moderate performance due to their statically indeterminate condition.

Aycardi et al. in 1994 studied scaled models for interior and exterior joints; they concluded that the improper beam bottom bar anchorage initiates the joint damage and with incremental loading, this damage reaches the column side. In order to study the joints prone to shear failure, Pantelides et al. in 2002 investigated six exterior joints without transverse reinforcement considering different anchorage condition. They concluded that the interaction of these two sources of deficiency affects such joint efficiency in a negative way. Pampanin et al. in 2003 tested RC joints similar to those existing in old buildings. They found that the negative impact of improper anchorage of beam bars was more obvious in exterior joints than in the other joints and hindered the utilization of full joint shear resistance. Kuang et al. in 2006 evaluated the effect of beam bar anchorage direction on exterior joint behaviour under cyclic loading. They concluded that joint shear strength is clearly dependent on anchorage conditions. The two defects in joint reinforcement detailing (anchorage outside the joint and no transverse reinforcement) reduce its capacity by 50%. Joints with longitudinal bars bent inside as in **Fig. 4 (a)** produced better behaviour than joints with bars bent outside.



a) Inside hook b) Outside hook

Fig. 4. Exterior joints with beam's bars bent inside and outside (Kuang et al., 2006).

Hassan in 2011 conducted an experimental study on corner joints designed according to old RC codes without transverse stirrups. The key parameters considered were the beam longitudinal bars reinforcement ratio, beam to column depth ratio, column axial stress level, and loading regime (in two or three directions). He concluded that transverse reinforcement leakage initiated joint damage at early loading stages and the column bars buckling controlled the total specimen failure. Tsonos in 2007 noticed higher rate of strength deterioration in joints with variable axial stress levels than in joints tested with constant axial stress level. Based on the previous research work, it is noticed that joint shear stress should be controlled and kept within specific limits in order to avoid such brittle failures. Also, proper beam's bar anchorage is a key parameter for a joint to assure its ultimate capacity. In order to avoid the brittle damage of joints, Park et al. in 1975 recommended sufficient transverse stirrups to guarantee joints performance with higher efficiency.

Individual effects of some key parameters are discussed in the following paragraphs.

Influence of concrete compressive strength

As the developed diagonal compressive strut faces resistance from the concrete in the joint panel zone, Hasaballa in 2014 concluded that increasing the concrete strength from 30 to 70 MPa increases the sustained lateral load resistance by 36% for exterior joints; he observed that specimens with lower concrete strength developed their maximum lateral resistance earlier than those with higher concrete strength. Ehsani et al. in 1991 concluded that joints with higher strength concrete require more confinement due to its brittle nature. Dehkoedi et al. in 2019 tested joints constructed with higher material strengths, recording similar behaviour as normal joints with 27% saving in reinforcement used. In addition to that, they demonstrated an improvement in energy dissipation for such joints with identical reinforcement ratios.

Influence of beam reinforcement ratio

Shear stresses in the joint panel zone are initiated mainly from the bars passing through the joint (Park et al., 1975). Moehle in 2008 concluded that the unconfined exterior joints shear strength was equal to the shear stress demand from beam flexural capacity, with an upper limit of $12(f_c)^{0.5}$ depending on concrete compressive strength. Based on tests of interior joints, Alire in 2002 showed that joint shear strength is dependent on beam flexural strength with less enhancement of joints with reinforcement ratios greater than 2.4%. In addition to that, any increase in the percentage of beam reinforcement (ρ_b) increases the flexural stiffness of the anchored bars hook. The increased flexural stiffness of the hook provides better confinement to the joint concrete core and also accommodates the formation of a compression strut mechanism, which in turn increases the joint load carrying capacity. Kemp et al. in 1968 tested four beam column knee joints under the action of closing moment; they observed low efficiencies for specimens with high reinforcement ratios. To this end, Nilsson in 1973 specified 2% as an upper limit for the ratio of main reinforcement to assure ductile failure and to control the reduction in joint efficiency with high reinforcement ratio. Increasing beam reinforcement ratio (ρ_b) up to a certain limit did not show superior performance over joints with normal ratios.

Role of joint reinforcement

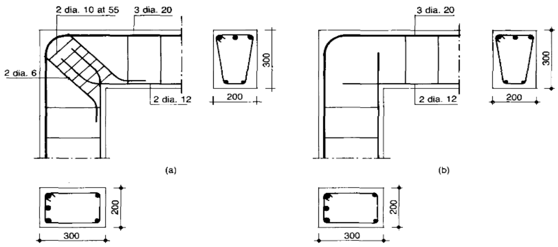
Hwang et al. in 1999 tested nine RC exterior joints to study the important role of the joint stirrups in resisting tensile stresses developed in the joint panel zone and in limiting joints crack width. They concluded that unreinforced joints constructed with high strength concrete can exhibit moderate seismic performance. Tomohiko et al. in 1995 studied RC interior joints and found that the increase in joint shear reinforcement created a slightly better bond situation along the column and beam longitudinal reinforcement in the joint.

Effect of transverse spandrel beam confinement

Many researchers reported a strength improvement of unconfined exterior BCJs by adding transverse concrete stubs (parts from perpendicular spandrel beams). Similar conclusions were reported by Megget et al. in 1971. He indicated that the transverse beams confined the joint core concrete and enabled the beam hinging to occur instead of joint shear failure. Topcu in 2008 observed that spandrel beams increased the joint shear capacity of subassemblies by about 15-20%, but they did not affect the bond-slip characteristics of inadequately anchored longitudinal beam bottom bars. ACI 352-02 suggests for an exterior reinforced joint with spandrel beams on both sides, a 25%-33% improvement in joint shear strength, because of the lateral beam presence. Hassan in 2011 supported the opinion of the beneficial nature of lateral beams if they are provided on both opposite joint sides. Cheung et al. in 1991 investigated the improvement in BCJs performance due to slab contribution; they recorded increase in beam flexure strength and limitation in its strength degradation after peak strength. To utilize these benefits, slabs rebars within the effective flange width should be properly anchored.

Beam and column rebars anchorages

As observed from previous research, beam and column longitudinal rebars may be anchored by one of these anchorage techniques: a standard hook (90 and 180 degrees), a mechanical headed end, or U-shaped ends. Sung et al. in 2007 compared joints with headed bars with joints with hooked bars; they observed that a BCJ with headed bars performs as well as the one with conventional hooked bars. Thompson et al. in 2002 investigated headed bars usage in exterior joints; they noticed that joints with headed end showed a good response compared to the hooked bars in terms of strength, deformability, and energy dissipation. Rajagopal et al. in 2014 discussed innovative joint designs that can reduce congestion of reinforcement without compromising strength, ductility, and stiffness. They tested six beam column joints. The specimens were divided into two groups; one group has standard conventional shear ties, and the other group with additional X-type cross bars. Each group has three specimens according to the anchorage detail; T- type mechanical anchorage (headed bar) and standard conventional 90° bent are used. They concluded that using T-type mechanical anchorage in combination with X-cross bars improves the performance with an increase in the load carrying capacity, ductility, and stiffness together with a reduction in reinforcement congestion. This is attributed to the tension in diagonal bars perpendicular to the joint diagonal crack; this helps in limiting the main diagonal crack width. Wallace et al. in 1998 tested two exterior joints; they concluded that the use of headed anchored bars instead of standard hooks in an exterior BCJ is a new relevant option. Ibrahim et al. in 2008 tested five exterior joints to study the effect of using double-headed studs as shear reinforcement instead of conventional closed stirrups. They concluded that using double-headed studs reduces joint steel congestion and improves joint shear resistance. As a conclusion, a beam-column joint with headed bars performs as well as (and even better) a joint with conventional hooked bars in terms of ultimate capacity and failure mechanisms. Wallace et al. in 1998 examined experimentally the RC knee joints behaviour. They concluded that the performance of joints with headed bar ends was as good as (or even superior) the joints constructed with conventional 90° hooked anchorages. Zouzou et al. in 1993 proposed confining stirrups for the diagonal strut in the joint region as shown in **Fig. 5 (left)**. These stirrups resist the splitting stresses formed inside the strut. The overall ductility of the joint is improved by moving the cracks from the strut region to be relocated outside the joint core.



a) Confined strut b) Unconfined strut

Fig. 5. Details for specimens with and without confined strut (Zouzou et al., 1993).

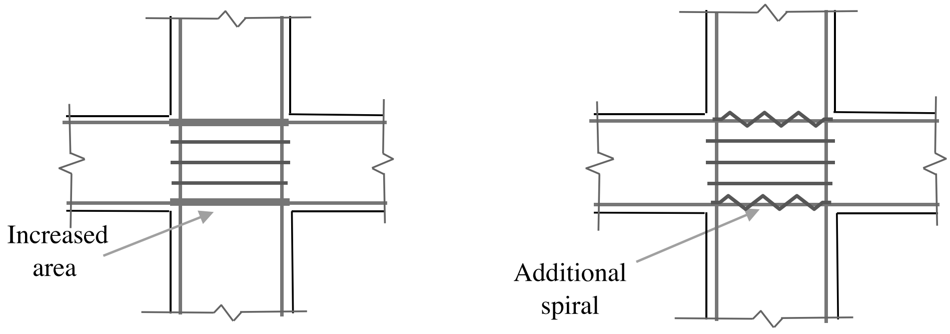
Luo et al. in 1994 concluded that specimens' flexural failure can be achieved using a low reinforcement ratio and a large bending radius of the hooked bars relative to the column effective depth. Francesco in 2015 studied knee joints under a closing moment and concluded that the headed end is very efficient and offers a more flexible alternative compared to the traditional hooks. A lot of research studies described the response of joints in terms of the ratio of the moment reached at joint failure to the ultimate moment of the weakest adjacent flexural member (this ratio is called the "joint efficiency factor"). A value higher than one is acceptable; this indicates that failure will be by flexure of the adjoining members. The joint should not be the weakest component in the frame, because their behaviour influences the whole structure's performance in terms of strength and deformability. The outcomes from these experimental tests provide a wider understanding point of view on the joints design and detailing through the discussion of different key parameters effect on joint resistance. As the previously mentioned experimental testing was expensive in time and cost, the numerical modeling of BCJs as a cheap and quick technique is presented in the following section.

MODELING OF BCJs

The development of analytical models to represent BCJs response is an important objective for many researchers. Joints brittle failures due to high shear stresses or anchorage slippage of longitudinal bars are also important to be modelled (Hassan, 2011). One approach that may be used to model BCJ behaviour under different loads is the one exploiting strut-and-tie model STM. Finite Element modeling is another possible choice; it can often give a basic idea of what behaviour may be expected in different situations. A new analytical concept by Hitoshi in 2001 is also available to model different BCJs. Hitoshi proposed a quadruple flexural resistance using general flexural equations to model the two possible joint failure modes: joint shear failure and beam failure. With his models, in order to avoid joint brittle shear failure, he proposed two approaches:

1- Increase joint moment capacity by increasing rebars area in the joint as shown in **Fig. 6(a)**.

2- Provide additional spiral to improve anchorage capacity inside the joint as shown in **Fig. 6(b)**.



a) Increased joint moment capacity b) Increased anchorage capacity

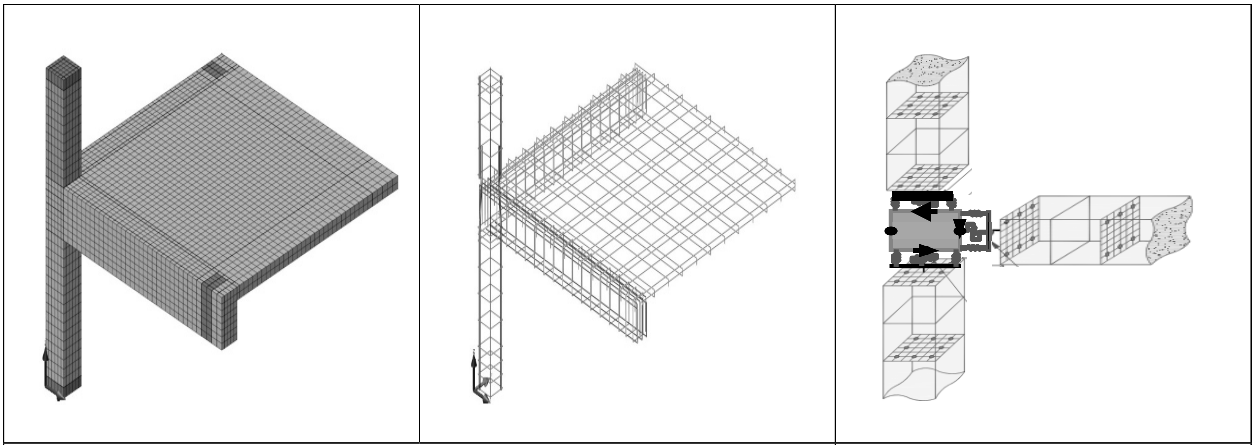
Fig. 6. Innovative reinforcement details for BCJ by Hitoshi, 2001.

Azimi et al. in 2014 proposed continuous rectangle spiral transverse reinforcement to improve the joint ultimate lateral resistance, ductility, and energy dissipation capacity.

Joint finite element models

Finite element software packages are available for creating and solving models simulating joint responses, such as ANSYS, ABAQUS, DIANA, ATENA, MASA, LS-DYNA, and OpenSees. A summary of research on numerical modeling of RC beam-column joints using different packages is presented in **Table 2**. This table presents the used verified cards in each software in order to have references for any further numerical work.

It is noticed from this survey that ANSYS has many capabilities for RC modeling; a drawback is that concrete solid element nodes have to be identical (in coordinates) with other element nodes (reinforcements and lamination). Compression softening in the concrete constitutive relationship and crack width verification are not available in ABAQUS. Despite the overall success of the developed model with DIANA, a reformulation for the unloading and reloading behaviour of concrete is needed to improve the energy dissipation characteristics of concrete structures under cyclic loading. For detailed modeling purposes, the first six packages were used successfully. For simplified modeling, OpenSees was used as it can go around many details in the joint with a reasonable accuracy in relevant run time.



a) Joint detailed model (concrete, rebars) | b) Joint simplified model

Fig. 7. Different BCJs modeling alternatives.

Among the previously mentioned software, DIANA and OpenSees have the possibility to handle in a good way the steel-concrete interaction, which consequently gave closer results to the experimental observations. The others assume complete bond between the two materials, which overestimate joints ultimate carrying capacity.

Table 2. Summary on the most used software packages in BCJs modeling.

Software package	RC components		Coupling mechanism	Joint type	Published papers
	Concrete	Rebars			
ANSYS	Solid 65 with 8 nodes	Link 8 with 2 nodes	Complete bond	2D exterior	39, 40, 41, 42
ABAQUS	C3D8R with 8 nodes	Truss T3D2 with 2 nodes	Complete bond	2D exterior, knee	43, 44
DIANA	Plane stress with 4 nodes, solid element with 8 nodes	Truss with 2 nodes, smeared layer	Bond-slip model	2D, 3D exterior, interior	45, 46, 47
ATENA	Plane stress with 4 nodes, solid element with 8 nodes	Truss with 2 nodes, smeared layer	Complete bond	2D exterior, knee	48, 36
MASA	Solid with micro plane material	Truss element with trilinear material	Discrete bond algorithm	2D exterior	49
LS-DYNA	Solid with damage material models	Beam and truss element with plasticity model	Contact 1-D Constrained beam in solid	2D exterior, knee	50, 51, 52, 53
OpenSees	Plane stress with 4 nodes	Truss with 2 nodes, smeared layer	Bond-slip spring	2D interior, exterior, knee	54

Analytical methods such as strut and tie method were used in combination with the numerical method to better assess joints ultimate capacity. The STM method also allows the evaluation of the ultimate capacity of different structural components at the discontinuity regions in RC members. Different STM research findings are presented and discussed in the following section.

BCJs strut-and-tie models

The strut-and-tie model (STM) is a common method used to evaluate the ultimate capacity of structural components at the discontinuity regions in RC members (Mac-Gregor et al., 2003). A sketch of the forces acting on a knee joint under a closing moment is shown in **Figure 8**, and an overview is provided in the following paragraphs, showing different research contributions.

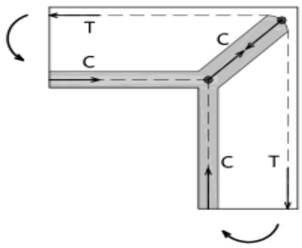
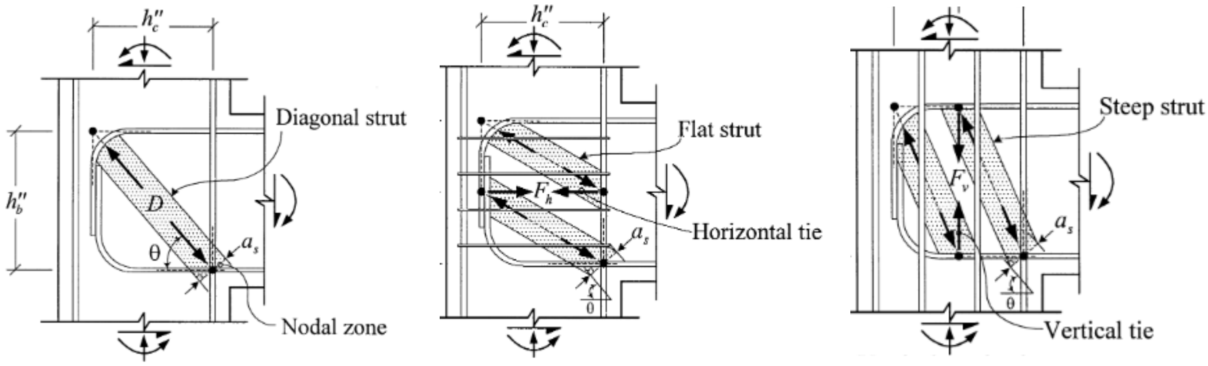


Fig. 8. Free body diagram for a knee joint subjected to closing moments (Francesco, 2015).

Hwang et al. in 1999 developed a model for predicting the shear strength of an exterior joint under lateral loading. By extending the principal of two mechanisms that are responsible for resisting the joint shear forces (diagonal strut and truss mechanisms), they proposed STM with three mechanisms: the diagonal, horizontal, and vertical mechanisms as shown in **Figure 9**. More details about the evaluation of the individual contribution of the horizontal joint reinforcement and the vertical column reinforcement are available in Hassan (2011).



a) Diagonal mechanism b) Horizontal mechanism c) Vertical mechanism

Fig. 9. Joint shear resistant mechanisms (Hwang et al., 1999).

Pantelides et al. in 2002 developed an STM based on their experimental results to represent the behaviour of unconfined exterior joints. First, they generated a global truss model for the entire specimen excluding the D-region (see **Fig. 10 (left))** and subsequently developed the D-region STM that best matched their experimental results (cracks distribution). The STM was characterized by the extension of struts to the nearest column hoop outside the joint and by the presence of three major compression struts within the joint. These three diagonals are initiated by the forces transferred from the anchored bar to the concrete by means of three mechanisms: bond at the bar's straight part, the bearing at the curved portion, and the bearing at the hook tail. They evaluated the failure modes of the STM based on the methods suggested by MacGregor et al. in 2003.

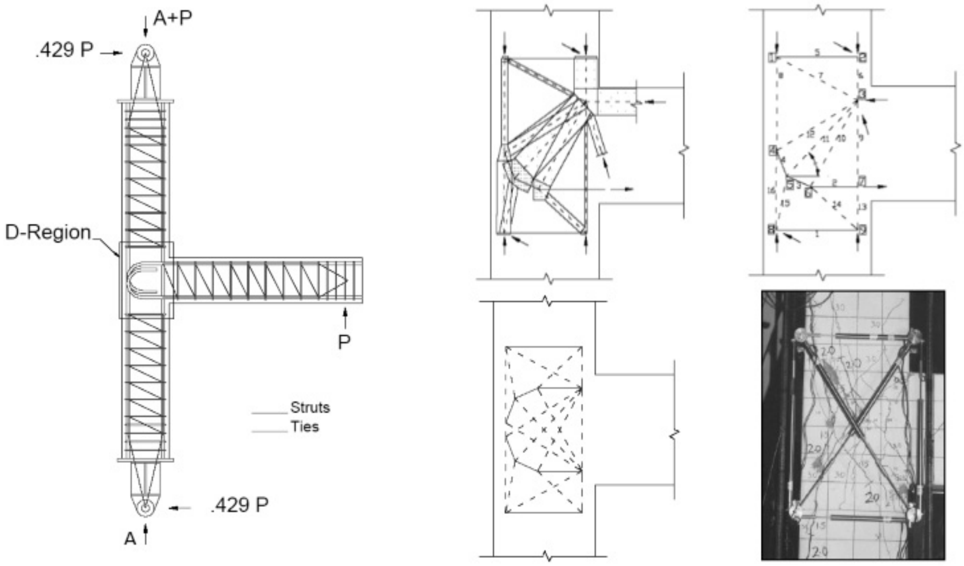


Fig. 10. Global strut-and-tie model for exterior joints (Pantelides et al. 2002).

Nicholas in 2005 constructed a new STM for a knee joint with improper reinforcement details under the effect of opening action (tensile stresses inside the joint). The column reinforcement was not fully anchored in the joint region and was terminated with a straight end, causing the absence of perfect anchorage. As a consequence, the flexural compression force in the top part of the beam was diverted inside the joint. Consequently, the joint flexural strength was reduced due to the shortening of the internal lever arm as a result of the compression force diversion as shown in **Figure 11**. Diversion of the compression force from the reinforcement path is attributed to the minimum force resisted by compression steel.

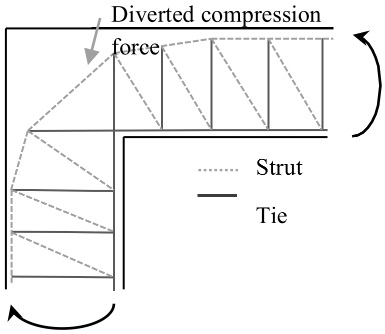
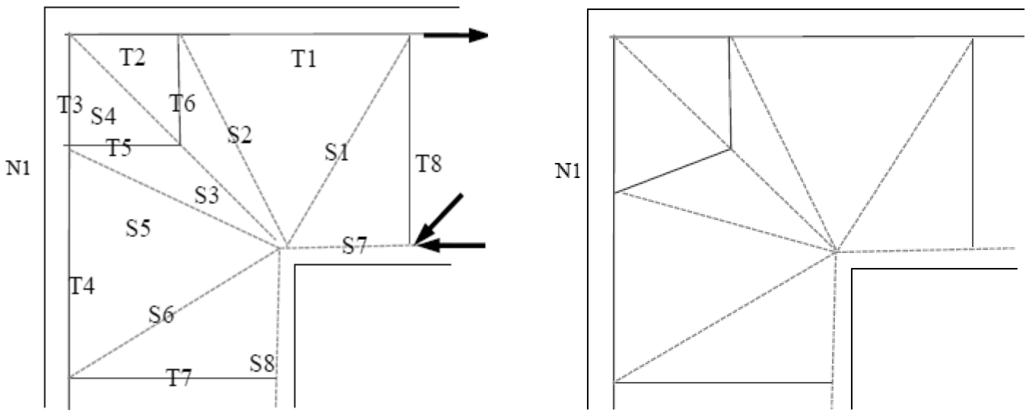


Fig. 11. STM with diverted compression force for knee joint.

Basem in 2018 developed a STM for a knee joint with improper reinforcement details under the effect of closing action (tensile stresses outside the joint). As a consequence, the joint compression force in the bottom part of the joint was diverted down from the joint towards the column. Consequently, the joint flexural strength was reduced due to the shortening of the internal force in the column outer bars as shown in **Figure 12**.



a) Model with perpendicular joint ties b) Model with inclined joint tie

Fig. 12. Refined STM models for knee joint under a closing action.

Vollum et al. in 1998 related the joint strength to the beam flexural capacity at the column face. They proposed models for exterior joints with and without stirrups. For joints without stirrups, the transmission of diagonal forces is assumed to take place only by one diagonal strut; for joints with stirrups, the joint three struts assumption is used to consider the contribution of the joints transverse reinforcements.

From the above review on modeling BCJs using STM, it was concluded that modeling joints with STM can produce adequate performance predictions for both proper and improper joints in terms of ultimate load capacity prediction, knowing that the location and orientation of any STM component can be changed and reoriented according to the joint reinforcement detailing and the expected cracking location. After the joints capacity assessment with different tools, some research interest was focused on the joint retrofitting and upgrading as presented in the following section.

BCJs RETROFIT

Kam et al. in 2008 and Iqbal et al. in 2015 utilized the post-tensioned external cables to confine the joint and improve its shear strength as presented in **Fig. 13(a)**. Shaaban et al. in 2018 used the ferrocement layers to retrofit joints; they noticed higher ultimate load and displacement capacity and moderate damage at failure load compared to the normal joints. Yasser in 2012 proposed the usage of post-tensioned metal strips for joints to improve their capacity and to achieve higher ductility as presented in **Fig. 13(b)**. The retrofit of BCJs with fastened diagonal haunch steel element was proposed by Giovacchino et al. in 2012 as an efficient technique, which effectively moves the critical section outside the joint (see **Fig. 13(c)).** Le-Trung et al. in 2010 examined different CFRP configuration to find the effective way in retrofitting nonseismic detailed joints. They recommended joint wrapping by X shape in combination with two layer strips on the column. The usage of hybrid fabric sheets (carbon and glass fiber) has been proven by Attari et al. in 2019 as a relevant alternative to improve joint ductility with relative less cost.

a) Joint with post-tensioned　　b) Joint with metal strip　　c) Diagonal haunch steel

Fig. 13. BCJs different retrofitting configurations.

Upgrading BCJs shear strength motivated many innovative retrofitting strategies, and increasing the confinement to the joint panel zone is one of the common points among these strategies.

CONCLUSION

The majority of the experiments and numerical models were on planar joints; the outcomes from these investigations are not relevant to 3D structures. From the literature review, the behaviour of exterior BCJs has been widely investigated under monotonic and cyclic loading. Many evaluation methods for BCJs behaviour are discussed starting from experimental testing for real size or scaled subassembly, to different numerical simulations utilizing available analysis techniques: detailed micro and simplified macro models with finite element method.

The main key parameters for joints have been discussed: i.e., Concrete compressive strength, fc; anchorage detailing of longitudinal beam rebars; axial stress level on the column; reinforcement ratio in beam and column and joint shear reinforcement. Some authors proposed different joint detailing configuration to move the critical section outside the joint towards the beam side away from the column face.

Analytical methods (STMs) were proposed based the flow of stresses inside the joint based on its rebars details. On one hand, FEA were used effectively to reproduce experimental results; on the other hand, more parametric studies were performed. More future works are needed to consider torsional effects on joints resistance due to slab presence or beam eccentricities. Investigations of large size BCJs behaviour are also needed to be highlighted as unusual failures are expected.

ACKNOWLEDGMENT

The author would like to thank Professor John Vantomme at Free University Brussels for constructive discussion and suggestions about the manuscript.

REFERENCES

Abdelwahed, O.H., Elnesr, O.M., EL-Ghandour, A.A. & Saad Eldin W.A. 2005. Behaviour of retrofitted beam-column joint with FRP, 11th Colloquium on Structural and Geotechnical Engineering, Cairo, Egypt., ID: E05RC38, 15 p.

ACI 318-08 Committee. 2008. Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary, American Concrete Institute, Farmington Hills, Michigan.

ACI 352R-02. 2002. Recommendations for design of beam-column connections in monolithic reinforced concrete structures, American Concrete Institute, Farmington Hills, Michigan.

Alire, D.A. 2002. Seismic evaluation of existing unconfined rc beam–column joints, MSc thesis, University of Washington.

Attaria N., Youcef Y. & Sofiane A. 2019. Seismic performance of reinforced concrete beam–column joint strengthening by frp sheets. Structures, Volume 20, August 2019, Pages 353-364.

Aycardi, L.E., Mander, J.B. & Reinhorn, A.M. 1994. Seismic resistance of reinforced concrete frame structures designed only for gravity loads: Experimental performance of sub assemblages, ACI Structural Journal, V. 91, No.5, pp 552-563,

Azimi, M., Azlan, B., Abdul Rahman B., Mahmood M., Iman F. & Reza Ho. 2014. Seismic Performance of RC Beam-Column Connections with Continuous Rectangular Spiral Transverse Reinforcements for Low Ductility Classes. The Scientific World Journal.

Basem, A., Bachir, B. & John. V. 2018. Reinforced Concrete Beam-Column Inverted Knee Joint Behaviour after Ground Corner Column Loss-Numerical Analysis. Latin American Journal of Solids and Structure. Vol 15 No 10.

Basem, A. 2018. Analysis of Inverted Knee Joints Related to Progressive Collapse Mitigation of Reinforced Concrete Frames. PhD thesis, Free university of Brussels, Belgium.

Bindhu K.R. & Jaya K.P. 2010. Strength and behaviour of exterior beam-column joints with diagonal cross bracing bars, Asian Journal of Civil Engineering (Building and Housing), V. 11, No. 3, pp. 397-410.

Cheung, P.C., Paulay, T. & Park, R. 1991. New Zealand tests on full-scale reinforced concrete beam-column-slab sub-assemblages designed for earthquake resistance, ACI SP123-1, American Concrete Institute, Detroit, Michigan.

Cote, P.A. & Wallace, J.W. 1994. A study of reinforced concrete knee joints subjected to cyclic lateral loading, Report No. CU/CEE 94/04, Dept. of Civil Eng., Clarkson Univ., Potsdam, NY, 143pp.

Danesh, F., Esmaeeli, E. & Alam, M.F. 2008. Shear strengthening of 3D RC beam-column connection using GFRP: FEM Study, Asian Journal of Applied Sciences, V. 1, No. 3, pp. 217-227.

Dehkordi, S., Davood M. & Pooya A. 2019. Effects of high-strength reinforcing bars and concrete on seismic behavior of RC beam-column joints. Engineering Structures VOL.183, pp:702-719.

Egyptian Code of Practice. 2017, Design and Construction Reinforced Concrete Structures 203/2017

Ehsani, M.R. & Alameddine, F. 1991. Design recommendations for type 2 high- strength reinforced concrete connections. ACI Structural Journal, **88**(3): 277-29.

EN 1998-1. 2004. Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC.

Francesco, M. 2015. Use of headed reinforcement bars in construction. PhD thesis, technical university of Madrid, Spain.

Giovacchino, G. 2012. Seismic Assessment of RC Exterior Beam-Column Joints and Retrofit with Haunches Using Post-Installed Anchors. PhD thesis, University of Stuttgart.

Hassan, E.M., 2011. Analytical and experimental assessment of seismic vulnerability of beam-column joints without transverse reinforcement in concrete buildings, PhD thesis, University of California, Berkeley, CA.

Hasaballa, M.H. 2014. GFRP-reinforced concrete exterior beam-column joints subjected to seismic loading. PhD Thesis, University of Manitoba, Manitoba, Canada, 393 p.

Hitoshi, S. 2001. New model for shear failure of RC beam-column connections, Journal of structural Engineering Division, ASCE, V.127, PP.152-160.

Hou, J. & Song L. 2016. Progressive collapse resistance of RC frames under a side column removal scenario: The Mechanism Explained. Int J Concr Struct Mater 10: 237.

Hwang, S. & Lee H. 1999. Analytical model for predicting shear strengths of exterior reinforced concrete beam-column joints for seismic resistance. ACI Structural Journal, Vol. 96, No. 5, 846-858.

Ibrahim, H. & Elbadry, M. 2008. Nonlinear 3D finite element analysis of exterior beam-column joints reinforced with double studs for shear resistance under cyclic loading, in Proceedings of the Annual Conference, vol. 4, pp. 2527–2537, Canadian Society for Civil Engineering.

Iqbal, A., Pampanin, S., Palermo, A. & Buchanan, A.H. 2015. Performance and Design of LVL Walls Coupled with UFP Dissipaters, Journal of Earthquake Engineering, 19:3,383-409, DOI:10.1080/13632469.2014.987406.

Işık, E & Özdemir M., 2016. The Effect of Strong Beam – Weak Column to Performance Based Assessment of RC Buildings. 1st International Mediterranean Science and Engineering Congress (IMSEC 2016), October 26-28, 2016, Adana/Turkey

James, B.D. 2013. Nonlinear finite element analysis of reinforced concrete exterior beam-column joints with nonseismic detailing. PhD thesis, Georgia Institute of Technology.

Kam, W. & Pampanin, S. 2008. Selective weakening techniques for retrofit of existing reinforced concrete structures. Proc. of 14th World Conference on Earthquake Engineering; 2008 12-17 Oct 2008; Beijing, China, 05-03-0074.

Kemp, E.L. & Mukherjee, P.R. 1968. Inelastic behaviour of concrete knee joints. The Consulting Engineer, pages 44–48.

Kuang, J.S. & Wong H.F. 2006. Effects of beam bar anchorage on beam-column joint behaviour Structures & Buildings journal **159**(2):115-124.

Kulkarni, S.A. & Li, B. 2009. Seismic behaviour of reinforced concrete interior wide-beam column joints, Journal of Earthquake Engineering, V. 13, pp. 80-99.

Le-Trung, K., Kihak, L., Jaehong, L., & Sungwoo, W. 2010. Experimental study of RC beam-column joints strengthened using CFRP composite. Composites Part B Engineering, **41**(1):76-85, DOI: 10.1016/j.compositesb.2009.06.005.

Lieping, Y., Zhe, Q., Qianli, M., Xuchuan, L., Xinzheng, L. & Peng, P. (2008). Study on ensuring the strong column-weak beam mechanism for RC frames based on the damage analysis in the Wenchuan earthquake. Building structure journal volume 11.

Li, B. & Tran, C.T.N. 2009. Seismic behaviour of reinforced concrete beam-column joints with vertically distributed reinforcement, ACI Structural Journal, V. 106, No. 6, pp. 790-799.

Long, X., 2013. Numerical study on reinforced concrete beam-column frames in progressive collapse; Nanyang Technological University, PhD thesis.

Luo, Y.H., Durrani, A.J., Shaoliang, B. & Yuan J. 1994. Study of reinforcing detail of tension bars in frame corner connections. ACI Structural Journal, **91**(4):486–496.

MacGregor, J.G. & Wight, R. 2003. Reinforced Concrete-Mechanics and Design, Fourth Edition, Prentice Hall, Inc., Upper Saddle River, NJ.

Mazzoni, S., McKenna, F., Scott, M. & Fenves, G.L. 2007. Opensees command language manual. Berkeley (USA): Pacific Earthquake Engineering Research Center, University of California. http://opensees.berkeley.edu/;

Mady, M.H.A. 2011. Seismic behaviour of exterior beam-column joints reinforced with frp bars and stirrups, PhD Thesis, University of Manitoba, Manitoba, Canada.

Megget, L. & Park, R. 1971. Reinforced concrete exterior beam-column joints under seismic loading. New Zealand Engineering, **26**(11): 341 - 353.

Mitesh S., Yogendra S. & Dominik H. 2018. Effect of strong-column weak-beam design provision on the seismic fragility of RC frame buildings. International Journal of Advanced Structural Engineering, Volume 10, Issue 2, pp 131–141.

Mostofinejad, D. & Talaeitaba, S. 2006. Finite element modeling of RC connections strengthened with FRP laminates, Iranian Journal of Science and Technology, Transaction B, Engineering, vol. 30, no. B1.

Moehle, J.P. 2008. Beam-Column Connections, PowerPoint Presentation, NEES GC Project: Mitigation of Collapse Risk of Older Concrete Buildings, Pacific Earthquake Engineering Website.

Mondal A., Ghosh S. & Reddy G. 2013. Performance-based evaluation of the response reduction factor for ductile RC frames. Engineering Structures VOL.56, pp: 1808-1819.

Nilsson, H.E. 1973. Reinforced concrete corners and joints subjected to bending moment - design of corners and joints in frames structures. Document D7:1973 National Swedish Institute for Building Research, Stockholm.

Nicholas, H. 2005. Nonlinear structural analysis using strut-and-tie models. PhD thesis, University of Auckland.

Park, R. & Paulay, T. 1975. Reinforced concrete structures, John Wiley and Sons, New York, 769 pp.

Pantelides C., et al. 2002. Assessment of reinforced concrete building exterior joints with substandard details, Technical Report PEER 2002-18, Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, CA.

Pampanin, S., Magenes G. & Carr, A. 2003. Modeling of shear hinge mechanism in poorly detailed R.C. beam-column joints, fib Athens, paper no. 171.

Peng, Z.Z. & Wang, Z.Q. 2010. Abaqus FEM analysis on knee joints in reinforced concrete frames. Journal of Chongqing Jiaotong University (Natural Science) **29**(5): 677-790.

Ravi, K. & Giovacchino, G. 2014. A case study on pre 1970 s constructed concrete exterior beam-column joints. Case Studies in Structural Engineering journal Vol. 1, Pages 20-25.

Rajagopal, S. & Prabavathy, S. 2014. Exterior beam-column joint study with non-conventional reinforcement detailing using mechanical anchorage under reversal loading Vol. 39, Part 5, pp. 1185–1200. Indian Academy of Sciences.

Salah, E. & Wai-Fah C. 2017. Structural Concrete: Strut-and-Tie Models for Unified Design.1st Edition. CRC Press, Published September 27.

Shaaban, G. & Mohamed, S. 2018. Finite element modeling of exterior beam-column joints strengthened by ferrocement under cyclic loading. Case Studies in Construction Materials 333–346

Shaabana, G. & Osama, A. 2018. Experimental behaviour of full-scale exterior beam-column space joints retrofitted by ferrocement layers under cyclic loading. Case Studies in Construction Materials 8.

Sung, C.C., Sung, H.L., Thomas, H.K., Bohwan, O. & Wallace, J.W. 2007. Mechanical anchorage in exterior beam-column joints subjected to cyclic loading. ACI Structural Journal, **104**(1):102–113.

Tavarez F.A. 2001. Simulation of behaviour of composite grid reinforced concrete beams using explicit finite element methods, MS thesis, University of Wisconsin-Madison.

Thompson, M.K. 2002. The anchorage behaviour of headed reinforcement in CCT nodes and lap splices. PhD thesis, The University of Texas at Austin.

Tomohiko, K. 1995. Influence of parameters on shear strength of interior beam-column joint, Proceeding of AIJ Annual Meeting, C-2, pp109-110.

Topcu, I., 2008. Experimental research on seismic retrofitting of r/c corner beam-column slab joints upgraded with CFRP sheets, MSc Thesis, Graduate Program in Civil Engineering, Bogaziçi University.

Tsonos, A.G. 2007. Cyclic load behaviour of reinforced concrete beam-column sub assemblages of modern structures, ACI Struct J; **104**(4):468-78.

Vafaei M., Mahmoud B. & Sophia C.2019. The relative importance of strong column-weak beam design concept in the single-story RC frames. Engineering Structures, Volume 185, 15, Pages 159-170

Vollum, R.L. 1998. Design and Analysis of Exterior Beam Column Connections, PhD Dissertation, Imperial College of Science Technology and Medicine-University of London.

Wallace, J.W., McConnell, S.W., Gupta, P. & Cote, P.A. 1998. Use of headed reinforcement in beam-column joints subjected to earthquake loads. ACI Structural Journal, Vol. 95, No. 5, 590-606.

Wight, J.K. & Durrani A.J. 1985. Behaviour of interior beam -to-column connections under earthquake -type loading. ACI Journal proceedings, **82**(3): 343-349,

Yasser, H. 2012. Seismic strengthening of deficient exterior RC beam-column sub-assemblages using post-tensioned metal strips. PhD thesis Faculty of Engineering of the University of Sheffield.

Yihai, B. & Lew, H.S. 2014. Modeling of reinforced concrete assemblies under column-removal scenario. Journal of Structural Engineering, **140**(1):04013026.

Zouzou, A. & Haldane, D. 1993. Detailing reinforced concrete closing corner joints for ductility. Structures and Buildings, **99**(1): 43–48.