Exterior Type-2 Wide Beam - Column Connection: An Overview

Vivek V S, Nithin Mohan

Abstract— In regions with a low to moderate level of seismicities such as Hong Kong, Italy, Spain, and Australia, it has been a widespread practice to utilise RCMRF with wide beams as the primary structural system for resisting lateral seismic loads. The design and construction of such structural systems are efficient and profitable. However, the resistance of the beam-column connections in this structural system against lateral earthquake loading is the major concern of structural engineers around the world. The exterior wide beam-column connections are not only susceptible to joint shear failure but also they are highly vulnerable to failure of the spandrel (transverse) beam in torsion. This paper presents the literature review on exterior type-2 wide beam-column connection

Index Terms— Wide beam-column connections, Spandrel beams, Torsion, Shear

1 Introduction

Reinforced concrete moment-resisting frames (RCMRFs) have commonly been used for low-to-moderate rise buildings in seismic prone regions. RCMRFs can perform well when subjected to strong earthquake ground motions if they are properly designed and detailed to dissipate the seismic input energy through deformations in the inelastic range. The connections between beams and columns thus become critical components. In typical RCMRF connections, the width of the beam does not exceed the width of the column (conventional connection). However, in most regions of moderate to low seismicity around the world, such as Australia, Hong Kong, and the majority of European countries, RCMRFs with wide beams have been extensively used.

Although the construction practice of wide-beam frame systems has been proven to be efficient and cost-effective, the resistance of the wide beam-column joints against lateral earthquake loading is the main concern of the structural engineers around the world. The exterior wide beam-column connections are not only susceptible to joint shear failure but also they are highly vulnerable to failure of the spandrel (transverse) beam in torsion. Torsion in a spandrel beam is produced by a wide beam's longitudinal bars that anchored outside the column. The results of tests on both exterior and interior wide beam-column connections, without reinforcement on transverse beams, showed that the transverse beams underwent severe torsion cracking, and the ductility and ultimate energy dissipation capacities of the wide beam were found to be much reduced. The existing test database of wide beam-column connection is insufficient, and it cannot address all behavioural aspects of the connections. Unfortunately, the numbers of tested specimens in previously published studies are very limited and various local reinforcement detailing and material properties are involved in the design and construction, which makes it difficult to extract a general design conclusion from the result.

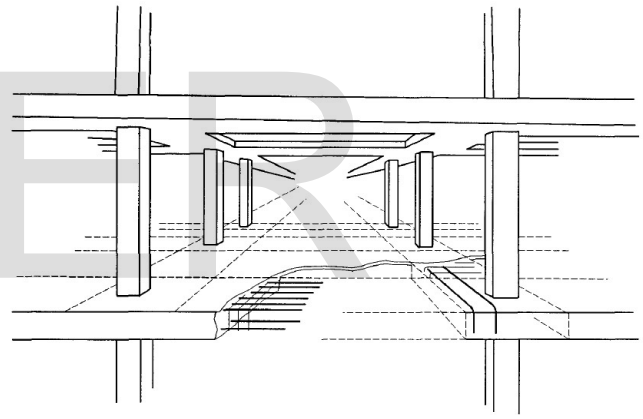

Figure 1: Reinforced Concrete Frame using Wide Beam Column Connection

Wide beams are largely preferred by architects as a primary gravity load carrying system because they allow more flexibility in the definition of spaces, and they are very effective in reducing the formwork, simplicity of repetition thereby accelerating the construction speed, and decrease in story height leading to reduction in the cost of construction. Compared to flat slab frames, it provides longer spans and more freedom on the column grid arrangements. However, they present several drawbacks when used in highly seismic regions as a lateral load-resisting system: (1) a deficient transfer of the bending moment from the wide beam to the column, (2) a low lateral stiffness, (3) a poor energy dissipation capacity. These drawbacks are primarily due to the fact that part of the wide beam longitudinal reinforcement is anchored in transverse beams perpendicular to the wide beams and adjacent to the column, rather than in the column core.

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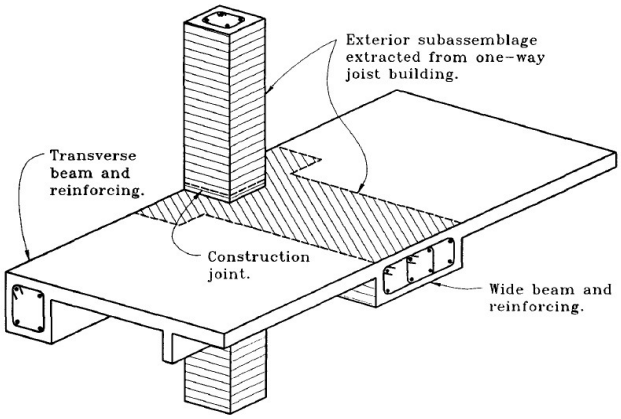

Figure 2: Wide Beam Column Connection

2 Background

In 1991, the American Concrete Institute (ACI)'s ACI 352R-91 [ACI, 1991] recommended that wide beam construction not be used in structures to dissipate energy inelastically in response to earthquake motions. In 1995, the same Institute's ACI 318–95 [ACI, 1995] permitted the use of wide beam-column connections in earthquake resistant design, if all longitudinal reinforcing steel of the beam not passing through or anchored in the column core was properly confined and if b_b was not more than b_c plus the distances on each side of the column not exceeding 0.75 h_b. In exterior connections, satisfying the first condition requires transverse beams whose depth h_s is commonly larger than h_b, in order to anchor the longitudinal flexural reinforcement of the wide beam.

In Spain, the pre-1994 national seismic code PDS-74 [SMC, 1974] contained no provision for the use of wide beams. The 1994 seismic code NCSE-94 [SMC, 1994] prohibited the use of wide beams in the southern regions of Spain when the design peak ground acceleration (PGA) was larger than 0.16 g (here g is the acceleration of gravity). The current Spanish seismic code NCSE-02 [SMC, 2002] permits the use of wide beams in earthquake-prone regions, if transverse beams with $h_s > h_b$ are provided in the exterior connections and if the position of the longitudinal reinforcing bars of the wide beam does not exceed b_c plus 0.5 h_b distances on each side of the column. In addition to the anchorage conditions and geometric limitations, the current seismic codes prescribe special reinforcement details aimed at attaining some degree of ductility at the wide beam ends.

The current codes of practice for structural concrete design, including ACI 318-14, NZS3101 and EN 1998-1, are based on the results of a small number of experimental studies. These codes impose special restrictions on the use of wide beam-column connections in high seismic hazard regions, such as geometrical constraints, special reinforcement details, and specific anchorage requirements. The restrictions are set mainly for minimising the shear lag in the formation of the full width plastic hinge in wide beams, thus preventing the beam from premature failure before flexural yielding. The main design approaches are the same as those of conventional beam-column connections, but the additional design requirements should be followed. It can be seen that the additional requirements for designing wide beam-column connections vary with different design codes of practice. ACI 318- 14 provides the largest beam width but the smallest effective joint width.

3 Classification Of Beam-Column Connections

Typical beam-column joints are defined as Type 1 and Type 2 joints, as per ACI 352R-02:

a) Type 1 Joints : these joints have members designed to satisfy strength requirements, without significant inelastic deformation. These are non-seismic joints.
b) Type 2 Joints : these joints have members that are required to dissipate energy through reversals of deformation into the inelastic range. These are seismic joints.

But in ACI 318-14, used another two categories, the first one is for beam-column joint that transfer moment to column shall satisfy detailing provision in chapter 15. The other category is for beam-column joint within special moment frames and in frames that not designed as part of seismic force resisting system in structures assigned to seismic design categories D, E, and F shall satisfy chapter 18.

3 Objective of the Study

This objective of this paper is to study published literatures related to the on Exterior Wide Beam Column Connections.

4 Exterior Type-2 Wide Beam Column Connections

As per ACI 352R-02, Exterior Wide Beam Column Connection are considered as Type-2 joint. At the exterior connections, transverse beams are commonly referred to as a spandrel beams. The exterior wide beam-column connections are not only susceptible to joint shear failure but also they are highly vulnerable to failure of the spandrel (transverse) beam in torsion. Torsion in a spandrel beam is produced by a wide beam's longitudinal bars that anchored outside the column. Thus, the transmitted beam forces may also induce torsion in the joint region, which will produce additional joint shear stresses. Therefore, the stress distribution and load transfer mechanisms in wide beam column connections are much more complex than in conventional beam-column joints.

Fig. 3 shows a statically determinate exterior wide beam–column connection with a column of size bcx hcx Lc and a wide beam of size bwx hbx Lb. The wide beam can be subdi-

vided into three parallel parts. The inside portion is connected di rectly to the joint, whereas the two outside portions are attached to the joint through the spandrel beam of size bsx hsx bo. Some of the longitudinal beam reinforcements are located at the outside portions (fig.3). These bars are anchored in the spandrel beams on two sides of the column. According to the weak beam–strong column concept, under the action of a lateral load plastic hinge damage is developed in the beam at the column face.

Fig.3 shows a free body diagram of the spandrel beam, with external forces acting on it. The resultant stress from the beam outside portion is transferred into the spandrel beam through tension forces along the longitudinal reinforcement bars ($T_{b;out}$), flexural compression forces ($C_{b;out}$), and the shear forces ($V_{b;out}$). The torsion in the spandrel beam (T_s) is produced by the eccentricity between the line of action of these forces and the spandrel beam shear center. Some previous researchers assumed that the beam bars passing outside the column, within a distance x on each side, could transfer the load to the joint through the formation of concrete struts and not by torsion. However, estimation of x is not a straightforward procedure, and requires engineering judgment. ACI 352R-02 (ACI 2002) recommends that all the beam bars anchored outside the column transfer their forces to the column face through torsion in the spandrel beam. Here it assumes that all the beam bars in the outside portion are effective in torsion.

5 Literature Reviews On Wide Beam Column Connections

Huang et al [1] tested full-scale exterior reinforced concrete wide beam-column joints with beam reinforcement ratios of 0.84%, 1.07% and 1.28% under reversed cyclic loading. Beam flexural failure was observed in the specimen with reinforcement ratio of 0.84%, while joint shear failure after beam yielding was detected in other two specimens. It is seen that the increase in the beam reinforcement ratio changed the failure modes of exterior wide beam-column joints from beam flexural failure to joint shear failure after beam yielding. In view of energy dissipation capacity, there is a threshold for the increase when the specimen behavior changes from beam flexural failure to joint shear failure. Also found that the column bars that located at the exterior face of the column were more sensitive to the slippage than those located at the interior face due to the different types of connection to the beam bars for exterior joints. No sign of spandrel beam torsional failure was detected in all specimens and the steel reinforcement of all spandrel beam remained elastic, which proves the validity of the design philosophy for spandrel beam in ACI codes.

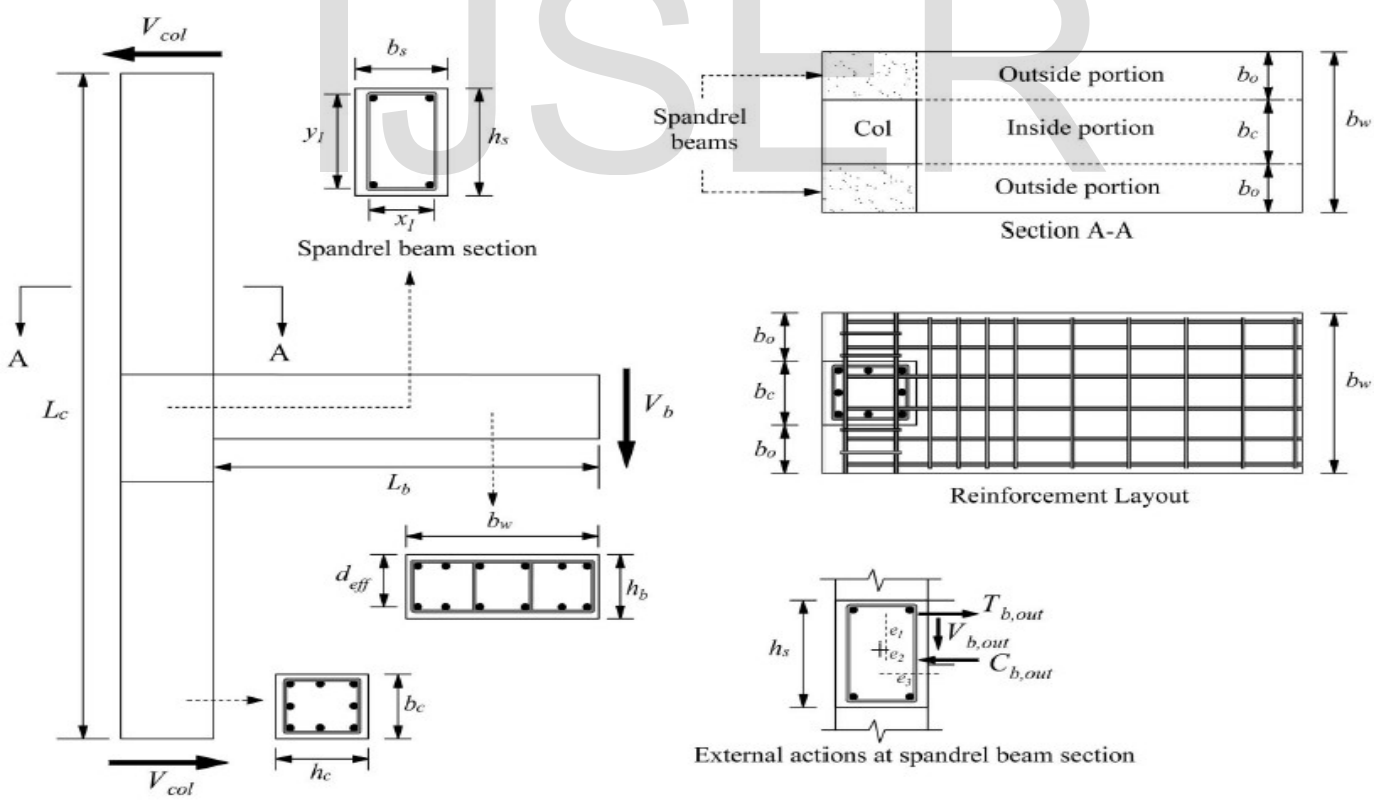

Figure 3: Typical geometry, reinforcement detail, and global equilibrium of an Exterior Wide Beam–Column Connection

Behnam Hamdolah et al [2] had done finite element analysis (FEA) of reinforced concrete wide beam-column connections using the theoretical context of the concrete damaged plasticity (CDP) model. The predictive capability of the model was verified by simulating the behaviour of four full-scale, exterior wide beam-column connections that were tested under reversed cyclic loading conditions. Results indicate that increasing the column dimensions and in particular column depth in wide beam-column connections, can significantly improve the seismic performance of the connection. From the structural point of view, increasing the column depth in the wide beam-column connections will result in contributing to the development of bigger compressive struts on the side face of the column, excessive anchorage length for the beam longitudinal bars, larger column-to-beam strength ratio and stronger transverse (spandrel) beams. It is found that increasing the beam depth while reducing the amount of beam longitudinal reinforcement has a significant effect on improving the response of the wide beam-column nonnections. The reason is that by increasing beam depth, spandrel beam become stronger and reducing the beam bar size results in less torsion in spandrel beam and less joint shear stress. From the numerical studies it is evident that show that axial compression load on the column enhanced the shear strength of the joint core through increasing the width of the diagonal compression strut within the core. A further increase in axial load, that is, beyond 0.3 $f'_c A_g$ had a negligible effect on the behaviour of connection. Anchoring more reinforcement inside the column core reduces the torsional demand on the spandrel beam.

Behnam Hamdolah et al [3] has done a set of experiments were performed on four large-scale exterior wide beam–column connections under a combination of a constant axial force and quasi-static reversed cyclic lateral displacements. The beam and column geometry and reinforcement detailing are identical for all four specimens, but the spandrel beam sizes and reinforcement ratios are different in each specimen. Detailed strain measurements, crack patterns, and data analysis indicate that the strength and stiffness of the spandrel beams could significantly change the expected response of wide beam–column connections. According to the results of the tests, the specimen with no reinforcement in its spandrel beam failed in brittle torsion with a significant reduction of strength and ductility compared to the expected capacities of the connection. Comparison of the test results indicates that the joint shear capacity of the specimen having a conventional deep spandrel beam did not significantly improve over the same specimen having a shallow spandrel beam. However, the results confirm that a well-reinforced wide spandrel beam substantially enhances both the joint shear capacity and the spandrel beam torsional strength of the connection.

Behnam Hamdolah et al [4] has done a set of experiments were performed on two full-scale exterior wide beam–column connections, which were tested under lateral quasi-static reversed cyclic loading. The control specimen had both longitudinal and transverse reinforcement in its spandrel beam. The second specimen was built in the same way but provided with post-tensioning force. The specimens were tested under a combination of axial force and quasi-static reversed cyclic lateral displacements. Results shows that the control specimen reached its expected beam flexural capacity at a drift ratio of 3%, and then the joint shear failure and spandrel beam torsional failure controlled the behaviour. The seismic performance of the specimen with a post-tensioned spandrel beam was considerably improved compared to the control specimens. The specimen sustained a 5% drift without any significant drop in strength. No signs of joint shear failure or spandrel beam torsional failure were observed in this specimen. The results indicate that adopting a post-tensioned spandrel beam can not only prevent torsional failure, but can also improve the joint shear capacity and displacement ductility.

Behnam Hamdolah et al [5] analytically developed an effective beam-width model of exterior wide beam-column connections using the equivalent - frame model representation, where the effect of torsion of transverse beams and flexure around the joint core is considered. The validity of the model is verified using flexural strength predictions of previously published tests in the literature, covering a wide range of design parameters. Combining the proposed effective beam-width model and the rational, analytical approach, a formula is presented for determining the beam-width limitation of exterior wide beam–column connections. For convenient application in practical design, the proposed beamwidth limitations of both exterior and interior connections are further simplified, and the relevant design curves and charts are presented.

Luk S. H et al [6] have conducted an investigation on the cyclic behaviour and force-transfer mechanisms of reinforced concrete exterior wide beam–column joints using computational simulation. Exterior wide beam specimens with different beam widths and reinforcement details are simulated under reversed cyclic loading using well-calibrated finite-element models with appropriate material constitutive laws and boundary conditions. It is shown that wide beam–column joints have good post-peak behaviour compared with conventional beam–column joints, which show severe pinching behaviour and low inherent ductility, although having higher strength and stiffness. Two load-transfer paths in wide beam–column connections have been identified, which are characterised by two struts with different inclined angles in the connecting wide beams and transverse beams. On the basis of research findings, reinforcement details and width limitation of wide beams are addressed in connection with the design of exterior wide beam–column connections.

Etemadi et al [7] have conducted a computational investigation was conducted using finite element model to evaluate the influence of geometric parameters on the behavior of exterior wide beam-column connections for reinforced concrete (RC) members under 5% lateral drift. After accurately verifying this model against existing experimentally recorded data, the force-displacement curves were determined for various dimensions of wide beam-column joints. The influence of dimension variation for wide beam on ductility, strength and energy dissipation of the exterior joint was quantitatively evaluated. The results demonstrated that the amount and configuration of steel reinforcement has significant influence on behaviour of wide beam-column connections. For widths ranging from 600 to 1000 mm, an increase in width can result in up to 36% reduction in ductility, 36% strength enhancement and 33% increase in energy dissipation. In addition to this, the effect of axial load on strength of structures was studied and the results showed that for the axial load increase from 150 to 350 kN resulted in a 30% reduction in strength.

Behnam Hamdolah et al [8] have conducted an experimental study that focused on the effect of beam width to column width ratio (or beam width ratio) on the seismic behaviour of exterior beam-column connections. Four specimens were designed, constructed and tested under reversed cyclic loading conditions. The primary test variables were the beam width ratio and the joint shear stress ratio (γ_d). The specimens were designed in conformance with ACI 318-14 and ACI 352R-02. They had beam width ratios of 1, 1.5, 2 and 2.5 and γ_d of 0.74, 1.12, 1.63, and 2.03. According to ACI 352R-02, the cd value should be lower than γ_n = 1.25 for joints confined on three faces. The results indicated that specimens with beam width ratios of 1 and 1.5 and γ_d of 0.74 and 1.12 were capable of supporting the complete formation of beam plastic hinges with no major cracks in the joint region. In contrast, specimens with beam width ratios of 2 and 2.5 and γ_d of 1.63 and 2.03 exhibited significant damage at the joint core. Torsional failure of the spandrel beam was also observed in specimen with beam width ratio of 2.5.

Huang et al [9] carried out an experimental investigation was carried out on two full-scale exterior wide beam-column connections, which are mainly designed and detailed according to ACI 318-14 and ACI 352R-02, under reversed cyclic loading. The ratios of the design shear force to the nominal shear strength of these specimens are 1.0 and 1.7 respectively, so as to probe into differences of the joint shear strength between experimental results and predictions by design codes of practice. Flexural failure dominated in the specimen with ratio of 1.0 in which full-width plastic hinges were observed, while both beam hinges and post-peak joint shear failure occurred for the other specimen. No sign of premature joint shear failure was found which is inconsistent with ACI codes prediction.

According to Kuang et al [10] reinforced-concrete wide-beam floor system is recognised as one of the most efficient beam-and-slab floor systems in buildings. However, potential advantages of the system as a lateral load-resisting structure are often ignored due to a lack of understanding of the seismic behaviour of wide beam–column connections. Design codes prescribe beam width limitations to minimise the shear lag effect on the formation of full-width plastic hinges and achieving the expected capacity. However, owing to insufficient experimental and analytical studies, empirical design formulas for the beam width limitation, with remarkably different results, have been implemented in different design codes. Parametric studies of the influence of key parameters on the behaviour of wide beam–column connections are conducted based on available test results. An effective beam-width model is analytically developed using the equivalent-frame representation, where the effects of torsion of transverse beams and flexure around the joint core are considered. The validity of the model is verified using flexural strengths of test specimens, covering a wide range of design parameters. Combining the proposed effective beam-width model and the rational analytical approach, a simple and efficient, yet accurate, design formula is presented for determining the beam width limitation of wide beam-column connections.

Behnam et al [11] carried out a set of experiments performed on two full-scale exterior wide beam-column connections. The specimens have the same dimensions and reinforcement detailing, except for the reinforcement detail in spandrel beam. The control specimen had both longitudinal and transverse reinforcement within the spandrel beam while the other specimen had no reinforcement in the spandrel beam. According to the results of the test, the failure mode in the control specimen was ductile with beam flexural hinging followed by joint and spandrel beam torsional failure, while it changed to the brittle torsional failure of spandrel beam in the other specimen. The specimen with no reinforcement in its spandrel beam exhibited brittle torsional failure with an average reduction of 37% in the wide beam flexural strength capacity compared to the control specimen. In addition to the experimental study, nonlinear three-dimensional finite element analysis was conducted to model the behaviour of tested specimens using monotonic loading analysis and to investigate the load transfer mechanism in wide beam-column connection. The results from both experimental and numerical investigation indicated that the level of joint shear stresses and the level of spandrel beam torsional stresses should be controlled to achieve an acceptable and adequate seismic performance.

Fadwa et al [12] carried out an experimental research to compare the behavior of two RC wide beam–column connections and two conventional beam–column connections when subjected to quasi-static cyclic loading. The specimens were full-scale connections and they were composed of two sets of interior and exterior joints. These specimens were designed in accordance with Syrian code of practice version 2006 (dependent on ACI 318 and ACI 352-R02 codes). Transverse beams in the wide beam–column joints, were also wider than the columns. Experimental results indicated that the hysteresis response of the wide beams was likely exhibited remarkable enhancement compared to that of conventional beams and the total energy dissipating capacity of a wide beam–column connection was higher than the conventional joint. Also it was found that by presence of the longitudinal reinforcement of the spandrel beam which was also a wide beam in the wide beam–column joints, flexural hinging mechanism in the wide beam was occurred instead of torsion brittle mode of failure.

Kuang et al. [13] studied the structural performance and cyclic behaviour of reinforced-concrete wide beam-column joints are by computational simulations with ABAQUS. Five wide beam-column joint specimens with the same column sizes but different beam widths and beam depths are simulated. Implicit finite element analyses are conducted, where concrete and steel reinforcement are modelled with 8-note 3-D solid elements and 2-node 3-D truss elements, respectively. The studies focus on the effects of beam widths and beam depths on the load transfer paths. It is shown that lesser crack opening occurs in wide beam-column connections; hence less pinched hysteresis loops are observed. The beam width has significant effect on the load transfer paths in wide beams and the corresponding joint cores. The simulated results also indicate that joint shear stress in wide beam-column connections is higher than that of conventional ones.

Fateh et al [14] have done an experimental investigation on the RC exterior wide beam-column joint when subjected to the gravity load up to failure is reported. This study was conducted by applying the concentrated gravity load on full scaled wide beam-column joints with same area of longitudinal reinforcement to resist for negative moment due to concentrated gravity load. The joints behaviour was considered by effect of different layout of beam longitudinal bars, existence of the shear link in connection zone, spandrel bar and width of the beam in terms of failure capacity, crack patterns, deflection and rotation. The results shown that the failure capacity of joints with concentrated longitudinal bars of beam that two-third of bars anchored in the column zone was 24% higher than even bar distribution. And also the existence of the shear links in connection area and spandrel bar to anchor the longitudinal beam reinforcements that were outside the connection area is higher than the other specimens without them.

Li et al [15] conducted experimental and numerical investigation that was carried out on three full-scale RC wide exterior beam-column specimens when subjected to seismic loads. Simulations of earthquake loadings were applied on to the specimens under quasi-static load reversals. It is found that Wide beam-column joints, when designed with suitable parameters, perform quite well in carrying the horizontal lateral loads as they can generally attain their strength and deformation capacity and concrete grades did not provide much influence the performance of the specimens. FE numerical investigation showed that the column axial load significantly influenced the seismic behavior of the wide beam-column joints with an improvement in their performance of up to 0.25 f_cA_g. When the column axial load level was 0.2 f_cA_g, the exterior wide beam-column joints exhibited an enhancement in strength of around 8 and 6%, respectively. The numerical study clearly suggests an improvement in joint shear stress by increasing the longitudinal bar anchorage ratio. The maximum joint shear stress experienced an enhancement of approximately 17% as the bar anchorage ratio was increased from 20 to 70%.

Benavent-Climent et al [16] have conducted an experimental study to investigate the seismic behavior of existing exterior RC wide beam-column connections designed according to construction practices in Spain during the 1970s, 1980s and 1990s. Two specimens with shallow spandrel beams lightly reinforced for torsion were subjected to moderate levels of gravity loading and quasi-static lateral cyclic loads until failure. First yielding of the wide beam longitudinal bars was observed at an average drift of about 2.2% of the storey height, and the ultimate drift ratio was about 4.5%. The failure of the connection was due to the development of severe torsion cracks in the spandrel beams (torsion members).

6 Conclusion

The literature shows that exterior wide beam-column connections are very vulnerable to seismic loading due to the sudden discontinuity of the geometry, inferior confinement conditions; and large induced torsional force on the spandrel beam. Moreover, previous studies have shown that the torsional behavior of spandrel beams strongly influences the overall seismic behavior of wide beam-column connections in terms of ultimate strength, stiffness, and energy dissipation capacities. The lack of torsional reinforcement in the spandrel beam was reported as one of the main reasons for the collapse of wide-beam frames in recent earthquakes.

Although the current design codes of practice [ACI Committee 318 (ACI 2014); ACI Committee 352 (ACI 2002); NZS 3101 (Standards New Zealand 2006); EC8, EN 1998-1 (European Standard 2004)] allow the use of RCMRFs with wide beams in regions of high seismicity, very little information is

available on their performance under seismic actions. In these codes, the primary design approaches for designing earthquake-resistant wide beam-column connections are similar to those for conventional beam-column connections. However, some additional design requirements such as beam width limitations and reinforcement details also need to be satisfied in order to minimize the lag in the formation of a full-width plastic hinge on the wide beam and to ensure proper stress transfer from the wide beam to the column. These imposed additional design requirements vary with different design codes, and as yet there is no uniform approach among the relevant codes for designing and detailing transverse beams against torsion.

Many researchers have investigated the influence of the transverse beam on the seismic performance of conventional beam-column joints, slab-column joints, and nonplanar beam wall joints. However, less attention has been paid to the effect of the spandrel beam on the seismic performance of exterior wide beam–column connections.

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