Fatigue Analysis of Beam Column Joint

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1 Introduction

Beam-column junction performance has a considerable impact on how Reinforced Concrete (RC) structures react to seismic occurrences. For nonseismically developed (NSD) structures, where transverse reinforcement is incredibly uncommon at beam-column joints, this is undoubtedly relevant. Previous seismic activities have proven that the failure of beam-column junctions has a negative effect on the general performance of RC buildings and can potentially cause their collapse.

A key factor in how reinforced (RC) structures react to seismic activity is the functionality of the beam column joints. Nonseismically designed (NSD) constructions refer to buildings that were not specifically designed to resist earthquakes. These buildings often lack the necessary features, such as transverse reinforcement, to withstand seismic forces. Transverse reinforcement is typically used in beam-column connections to provide additional strength and ductility to the structure. During an earthquake, the beam and column experience horizontal forces that can cause the beam to shift or rotate at the connection. Without proper reinforcement, this can lead to the failure of the connection and collapse of the structure. The most of the time, the behavior of joints is assessed at the level of the subassembly, where other sides of the column are hinge-supported and the contraflexure sites in a construction are typically

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found near the midpoint of the columns and beams. The vertical shear load applied to the beam tip occurs periodically. The first report of such tests was made by Hanson and Connor [1], who showed that joints without hoops can cause the subassembly to behave poorly under load displacement. The diagonal cracks that finally developed in the junction eventually resulted in a brittle joint shear collapse that left the transverse reinforcing bars of the beam unyielding. The things found out of this development spurred a frenzy of investigation into the empirical and numerical aspects of the dynamic response of beam column joints, results supported the early appearance of the JS failure. Being brittle and absorbing significantly less energy than a flexural failure characterized by steel yielding, this failure mode is understandably undesired in the seismic design philosophy. The literature has looked into the sub-assemblies' susceptibility to non-seismic detailing that has been used. They include lap splices in columns directly above the joint, joint cores without insufficient transverse or lateral reinforcement, and inadequate anchorage of the beam reinforcing reinforcement in the junction, to name a few. It is possible to conclude that the joint shear strength of beam-column connections decreases with an increasing aspect ratio by analyzing the joint shear strength values of these connections and their aspect ratios, as described in literature [2–4].

Buildings also feature longitudinal beams and integrally cast slabs, but much study has concentrated on two dimensional sub-assemblies. In order to effectively represent the joint shear behavior, it is essential to consider 3D phenomena such slab contributing and restriction of the longitudinal beams to the joint. This study examines how the aspect ratio affects the connections between 3D NSD external beams and columns that have transverse beams and slabs. The examination is carried out as part of a numerical analysis using the University of Stuttgart's MASA FE code.

2   Influence of Joint Aspect Ratio

The average notion is typically employed to assess the joint shear capacity. Simple technique for strain and stress According to design rules for new structures, the average active horizontal joint's shear stress must be kept under permissible bounds for minimizing the joint shear failure. FEMA 356 [5] contains suggested parameters for the necessary joint shear stress for analysis of the beam column joints for current RC structures that weren't built seismically. The principal tensile stress (pt) technique is a different model based on the same methodology. Acting joint stresses at the horizontal and vertical axes are converted into principal stresses using the Mohr circle theory. Priestley [6] provided initial joint cracking values of $p_t = 0.29f'c^{0.5}$ and final joint strength values of $p_t = 0.42f'c^{0.5}$ for 2-dimensional external joints with rebar bent in the intersection with a 90° angle hook. The CEB240 [7] recommends these values.

The joint shear strength's critical values should be determined while taking into consideration the following, though the aforementioned design rules did not take aspect ratio (alpha) into account. In his study of 2-Dimensional joints with the three
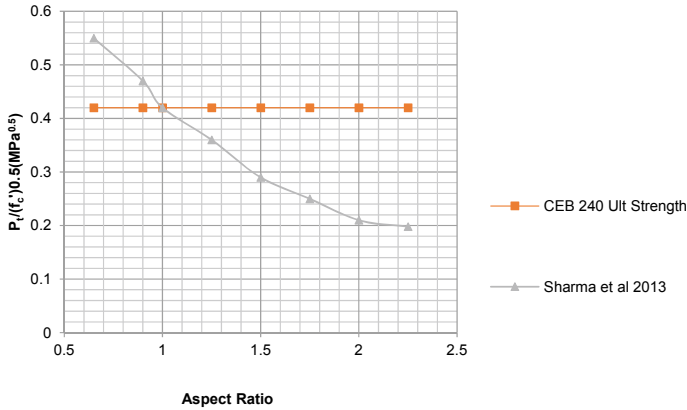
Fig. 1 Database containing information on beam-column connections with longitudinal beam bars bent to form exterior joints

distinct aspect ratios (1, 1.5, and 2), According to Wong [8], the joint shear strength rises with the ratio of the depths of the beam to column. Similar findings have been observed regarding corner joints between a longitudinal beam and slab, Park [2] and Hassan [3] both agreed. A data of 50 2D outer beam-column connections with bending beam transverse reinforcement has been constructed in order to better understand the influence of joint aspect ratio.

Figure 1 shows how a higher aspect ratio affects the joint shear strength. Internal twisting stresses within the beam and within the column combined to produce a transverse or lateral strut (S) in the joint wall itself when a descending shear force will be applied to tip of the beam [9].

The joint shear force V_{jh} which operate in the horizontal direction and joint shear force V_{jv}, which operate in the vertical direction are illustrated in Fig. 2c. The lateral joint shear force reaches horizontal stability at the middle of the joint panel and adjusts at this point the differential in between shear force with in column and the force applied in the transverse beam bars. Because the lateral force of diagonal strut S resists V_{jh}, the amount of compressive stresses in somewhat slant struts must increase to oppose the same V_{jh}. Figure 2 visually depicts it. Figures 2a and 2b additionally, it could be recorded that once diagonal fracturing in joint begins Situated between the steel reinforcing bars, the truss stabilizes.

The slab's presence deserves additional emphasis. The torsion of the transverse beam is believed to impart joint shear [10], which is said to provide a mechanism for resisting the tensile pressures in the slab bars. To calculate V_{jh} (as shown in Fig. 2c), the tensile force of the longitudinal beam bars (T_{sb}) and the force applied by the slab frames (T_{ss}) are combined. When calculating pt in this study, this information is taken into consideration.
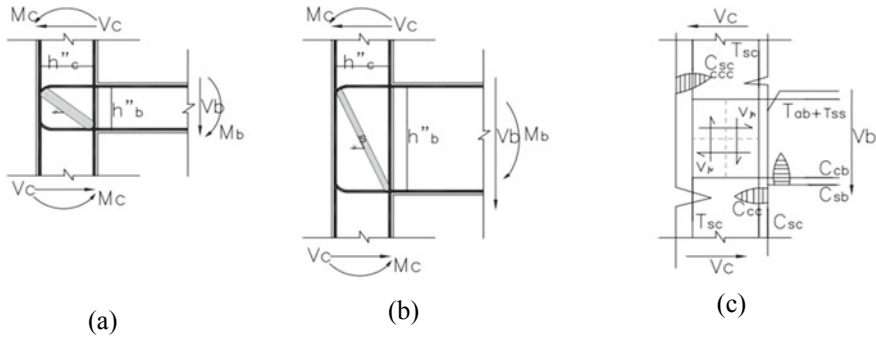
Fig. 2 Formation of diagonal strut for **a** $\alpha = 1$, **b** $\alpha = 2$ and **c** horizontal and vertical shear of exterior BCJ

3 Numerical Studies

3.1 FE Model

ANSYS v.22 is used to run the numerical simulations. The relaxed kinematic constraint micro plane model is the constitutive law for concrete [9, 11, 12]. Using 8-node hexahedral components with mesh widths ranging from 20 to 30 mm, we simulate concrete. Modeling of re-steel involves the use of 2-node elements of truss using a tri-linear uniaxial stress strain law. Lettow's bond connection components with zero width are used to illustrate the bonding between reinforcing steel and concrete.

3.2 Explored Connections (Beam-Column Joints)

In this work, the examined beam-column junctions are depicted in Fig. 3. The purpose of the study is to assess how the principal tensile stress pt has changed over time in relation to various aspect ratios. It is specifically looked at how the existence of transverse beams and slab affects how the pt trend for 3D joints differs from that for 2D joints. It should be noted that the behavior of the joints is typically analyzed under the assumption that the beam is uniformly pulled downwards, as would occur when the slab is in tension.

The sub-assembly of the beam-column joint and the example with a 400 mm beam level is shown in Fig. 4 along with its dimensions and reinforcing features. The 400×400 mm column cross section is consistently preserved, and aspect ratio is consistently altered by merely adjusting beam height. When the concrete coverings are 50 and 50 mm from the bar diameter and bar core., aspect ratio in Fig. 4 is equal
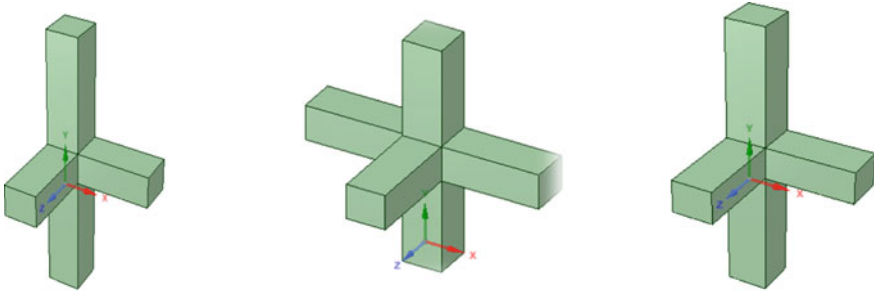
Fig. 3 Exterior BCJ; **a** 3D joint **b** Corner joint and **c** Edge joint

Corner Beam Details   Middle Beam Details   Column Details
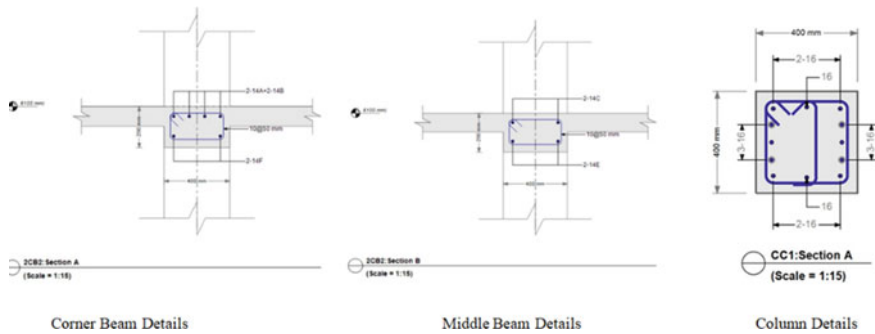
Fig. 4 Structural configuration and intricate features of beam-column joints

to 1.3. For every simulation, concrete cylinder with a 30 MPa compressive strength is used.

The longitudinal beam's transverse beam bars were similarly fastened with a 90° angle hook in the corner joint case. In view of an edge junction, the bars penetrate exactly through it. Bottom slab reinforcement bars are fixed straight, but the top slab reinforcement bars end together in 90° hook. The sub-width, assembly's which consists of the column and width of slab, is 1200 mm and for edge joint and 2050 mm for edge junction. The statistical simulations are summarized in Table 1.

Table 1 Outline of virtual simulations

Joint type	Aspect ratio			
3D	0.625	0.90	1.13	2.0
Corner	0.625	0.90	1.13	2.0
Edge	0.625	0.90	1.13	2.0
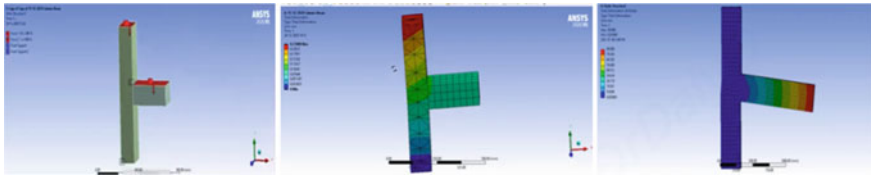
Fig. 5 Modelled Ansys members and failure pattern of edge beam and transverse beam

3.3 Formation of Cracks in 3D Beam-Column Joints

The simulated load–displacement curves illustrate the different stages of cracking, aiding in the comprehension of the behavior of the investigated beam-column connections. The various stages involved in the analysis of beam-column connections typically include the following: Joint shear cracking (J), flexural cracking in the column (C), torsional cracking in the transverse beam (T), flexural fracture in the loaded beam for two-dimensional joints (B), flexural fracture in the slab for three-dimensional joints (S), and flexural cracking at the onset of the slab (O) (T).

Regarding corner joint at the failure, many types of cracks visually represented in Fig. 5 along with the descriptions that are used in the subsequent load–displacement curves. The essential fracture width of 0.3 mm is represented by the red color on a plot of the primary tensile strain, or 11, which shows the cracks. The joint shear failure of the subassembly is accompanied by a large widening of the diagonal crack in the core of the joint. Due to the joint's horizontal expansion upon breakdown, vertical cracks progress on the back part of the joint. Furthermore, the longitudinal beam is torsionally stressed by the slab as evidenced by the helical fissures that run down its backside.

3.4 Without a Transverse Beam and Slab, a Beam-Column Joint (2D)

Figure 6 illustrates load–displacement patterns of 2D beam-column connections with different aspect ratios. The various cracking phases are also included to the curves. It is clearly seen that the curve loses stiffness with each new crack that forms. The earliest cracks in the beam are flexural ones, which affect all sub-assemblies. The curves demonstrate that as aspect ratios are increased, the stiffness of the beam rises and the number of cracks decreases. The increased moment of inertia of the beam is related to both outcomes. Additionally, the higher shear loads at the ends of the column are enhanced due to the increased shear strain on the beam, which results in flexural cracking in the column.
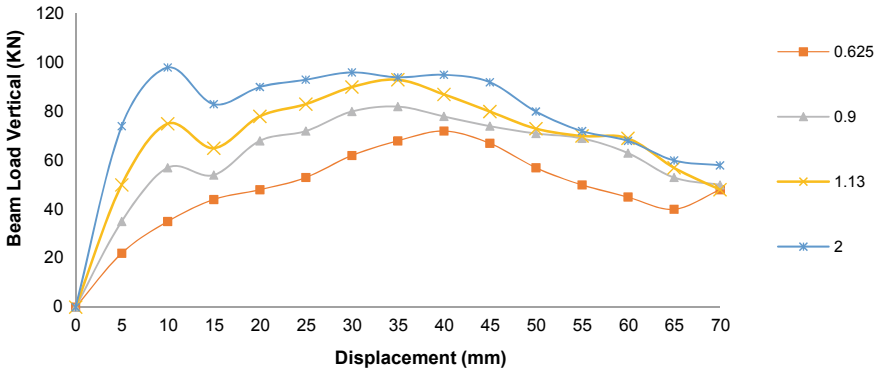
Fig. 6 The load–displacement (l-d) behavior of the 2D geopolymer beam-column (GBC) joint is illustrated through curves

The major tensile stresses over the aspect ratio are represented by the numbers in Fig. 7. The estimated values' prospective trend is also shown. They clearly show that Sharma's model fits them well [13].

As the aspect ratios increase, the primary tensile stress values (pt) for initial joint cracking and ultimate joint strength exhibit a similar trend to the vertical beam load. The examined 2D joints all experience shear failure.
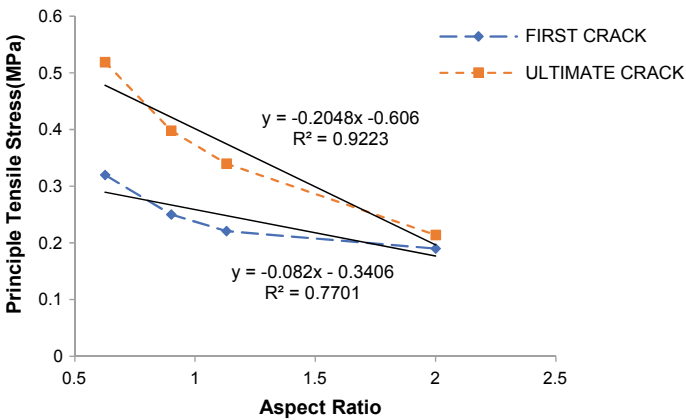

Fig. 7 Principle tensile stress to aspect ratio 2D GBC joint
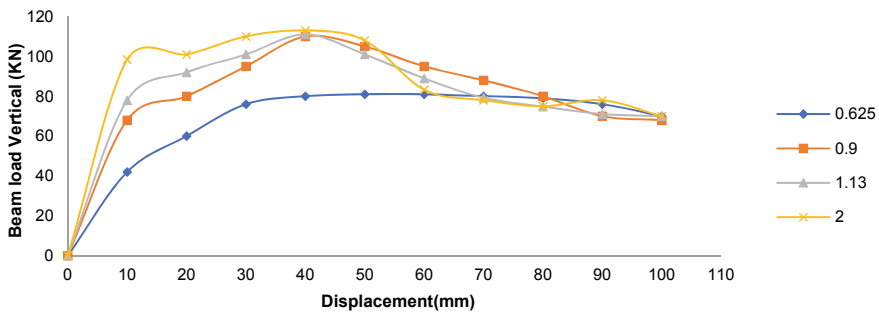
3.5 Beam-Column Joints (BCJ) @ Corner

Figure 8 displays the load–displacement behavior of edge beam-column joints with different aspect ratios of the lateral beam and slab. It is worth noting that the cross-sectional properties of the loaded beam and the transverse beam in the subassembly are identical. As a result, the torsional capacity of the transverse beam increases proportionally with the aspect ratio. Analysis of the load–displacement curves reveals that 3D beam-column joints are more prone to cracking compared to 2D joints.

In Fig. 5, it is possible to observe cracks caused by torsional forces resulting from the twisting of the transverse beam by the slab. These cracks start at the column and extend outward along the rear of the transverse beam. Upon closer examination, it has been found that as the aspect ratio increases, the torsional cracking appears at lower displacements and higher loads at the tip of the beam.

Nevertheless, the loads in the corner joint exceed those in the 2D joint, leading to excessive bending or flexural cracks in both the slab and column.

The load-carrying capacity of the slab and the restrictive effect of the transverse beam on the joint can account for the higher load values. It is also interesting to observe that, in comparison to 2D joints, the rigidity does not recover as quickly following the first joint crack. Particularly, for the aspect ratios of 1.7 and 2.3, this is true. The reason for this outcome could be attributed to the fact that tensile stresses in the slab bars decrease the ability of the struts to remain stable by increasing the tensile pressures that the joint shear must resist.

The values of the initial tensile stresses, maximum joint shear strength, and initial joint fracture are shown in Fig. 9, together with any potential changes. The critical values of pt are expected to be higher than for 2-dimensional joints due to 3-dimensional phenomena like slab involvement and restriction of the transverse beam and transverse slab toward joint. The decline of the tendency is, however, essentially the same.

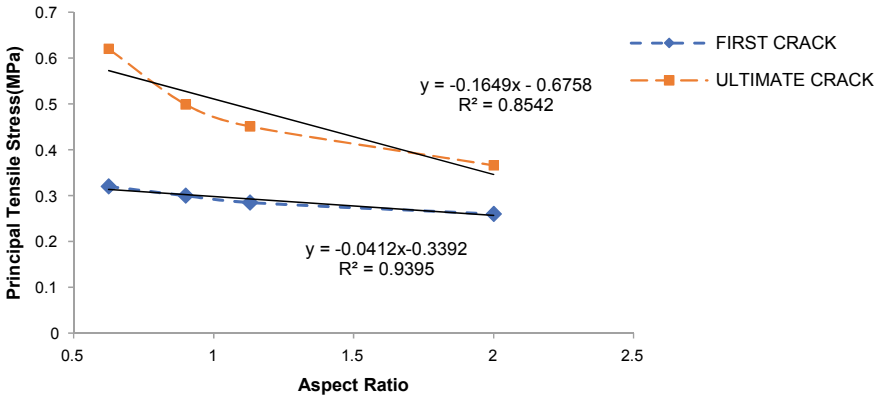**Fig. 8** Load–displacement curves for the corner joint of a 2D geopolymer beam-column (GBC) connection

Fig. 9 Principle tensile stress to aspect ratio 2D corner GBC joint

3.6 *Beam-Column Joints@ Edge*

Load–displacement behaviors of the end connections of beam-column joints are depicted in Fig. 10. Like the corner joint, which failed due to torsion of the transverse beam, the edge joint with an alpha value of 0.92 also undergoes failure. The torsional crack appeared to originate prior to the joint cracking, according to detailed examination. This proves that transverse beam's earlier failure prevented the joint's ultimate shear strength from being reached. However, the edge joint has a higher peak load than the corner joint, which also indicates that it has a higher ultimate shear strength. Like with the other aspect ratios, a joint shear failure results in a loss in the sub-ability assembly's capacity to carry loads. That the very first joint crack also happens first within those cases. Due to the edge joints' increased slab contribution, which causes a greater disturbance of the strut stabilization, the stiffness recovers after the initial joint crack less rapidly than at corner joints.

Figure 11 displays the computed primary tensile stress values (pt) for the analyzed edge joints. Only the pt at initial joint fracture is taken into consideration in the trends for the scenario with alpha identical to 0.92 due to the transverse beam's earlier torsional failure. The findings indicate that the ultimate shear capacity of corner and 2D joints is less prone to degradation.

According to the available data, its transverse beam and corresponding slab possess the largest an impact on how edge joints behave during joint shear. The slab contribution has increased and a transverse beam is now projecting into the joint from two sides. For example, the primary tensile stress threshold that leads to the initial fracture of the joint and Priestley's suggested aspect ratio of 1 is 0.29 fck 0.5, however the value rises to 0.46 fck 0.5 and 0.6429 fck 0.5 for the corner and edge joint, respectively.
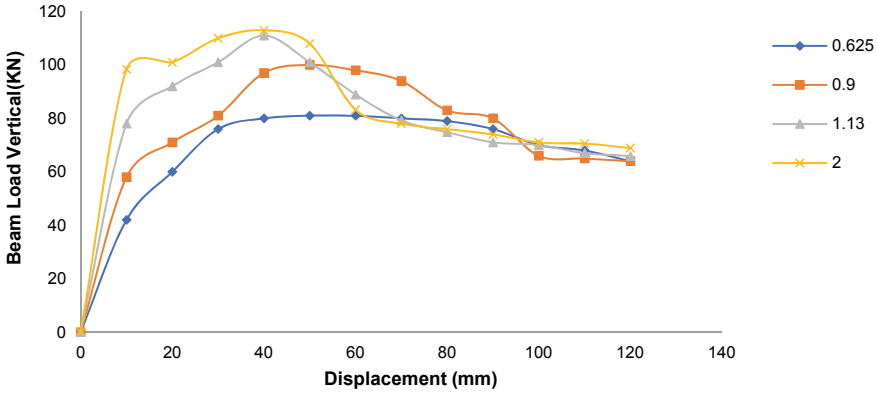
Fig. 10 Load displacement (ld) curves for 2D geopolymer beam-column (GBC) edge beam joint
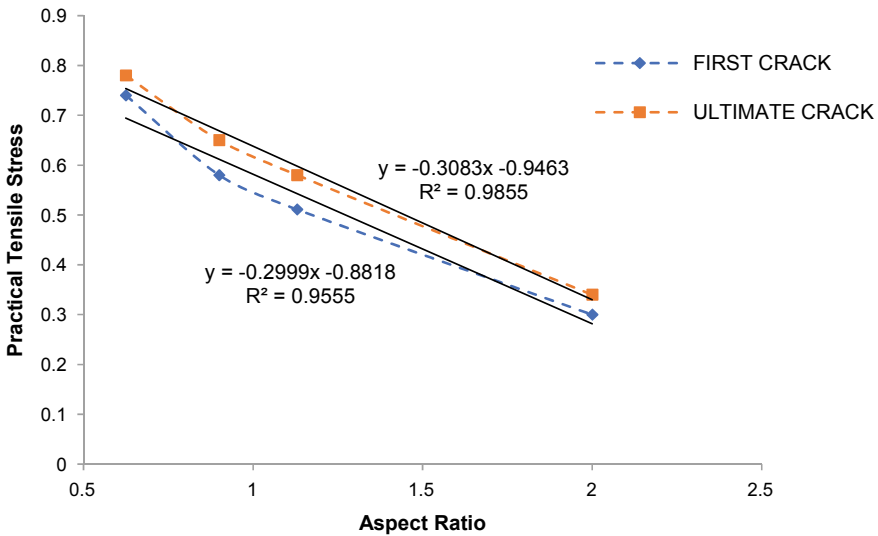

Fig. 11 Practical tensile stress to aspect ratio of 2D Edge GBC joint

4   Conclusions

A 3D beam-column joint's shear strength was evaluated by utilizing finite-element analysis to investigate the impact of the joint aspect ratio. It is well known that the primary tensile stresses for 2D joints and 3D joints have a variety of critical values suggested by the literature. This has happened as a result of the slab's involvement and the joint's limitation by the longitudinal beam and the slab. As the slab bars experience increasing tensile stresses, they transfer these stresses to the joint through the transverse beam's twisting action, thereby intensifying the shear resistance demands

on the joint. According to an example [4], the maximum joint shear resistance may not be reached when the transverse beam has relatively low torsional resistance, which was frequently the issue for low aspect ratios, because of prior torsional collapse of the lateral or transverse beam. Similar to 2D joints, the investigated 3D joints also experience a decrease in shear resistance as the aspect ratio increases. Upon comparing the reduction in ultimate joint shear capacity of 2D joints and corner joints to the acquired pt values trend line, it was observed that the decline in edge joints is slightly more significant.

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