INFLUENCE OF THE ASPECT RATIO ON THE SHEAR STRENGTH OF 3D BEAM-COLUMN JOINTS

EINFLUSS DES SEITENVERHÄLTNISSES AUF DIE SCHUBTRAGFÄHIGKEIT VON 3D-RAHMENKNOTEN

Margaritis Tonidis[1], Akanshu Sharma[1,2], Josipa Bošnjak[1]

[1] *Materials Testing Institute (MPA), University of Stuttgart, Otto-Graf-Institute*

[2] *Institute of Construction Materials, University of Stuttgart*

SUMMARY

The paper investigates the influence of the joint aspect ratio (ratio between beam depth to column depth) on the shear strength of exterior non-seismically designed reinforced concrete beam-column joint sub-assemblies with transverse beams and slab. Three-dimensional numerical (FE) analysis is performed employing the microplane model for concrete. The behavior of a joint without out-of-plane members (2D), a corner joint with one transverse beam and slab and an edge joint with two transverse beams and slab has been investigated with respect to four different aspect ratios: 0.9, 1.3, 1.7 and 2.3. The attained loads at first joint shear cracking and ultimate capacity are converted into principal tensile stresses. For all investigated joints, it has been found that the critical principal tensile stresses at first joint shear cracking and ultimate joint shear capacity decrease with higher aspect ratios.

ZUSAMMENFASSUNG

Der Artikel befasst sich mit dem Einfluss des Seitenverhältnisses (Verhältnis Balkenhöhe zu Stützenhöhe) auf die Schubtragfähigkeit von äußeren, nicht erdbebengerecht entworfenen Stahlbetonrahmenknoten mit querlaufenden Balken und monolithisch verbundenen Platten. Die Untersuchungen werden im Rahmen der Finiten-Elemente-Methode (FEM) durchgeführt, in der das Microplane Modell als das konstitutive Gesetz für Beton benutzt wird. Die numerischen Simulationen zeigen, dass die Schubtragfähigkeit für zwei-dimensionale als auch für drei-dimensionale Rahmenknoten mit steigendem Seitenverhältnis abnimmt.

1. INTRODUCTION

The performance of the beam-column joints is a decisive parameter regarding the behavior of reinforced concrete (RC) structures exposed to seismic events. This is particularly true for the non-seismically designed (NSD) structures, where commonly the beam-column joints are devoid of transverse reinforcement. Past earthquakes have shown that the failure of beam-column joints adversely affects the overall performance of RC buildings in such a way that they even may collapse.

The susceptibility of such joints in NSD structures originates from the drastic change of the moment diagram in the structure under lateral loads compared to gravity loads. In the case of lateral loads, the beam-column joints are surrounded by moment reversals. The steep gradient of the moment diagram within a relatively short length (column depth) results in high shear stresses in the joints.

In the past decades, NSD joints have received considerable attention. In most cases, the behavior of joints is examined on the sub-assembly level, where both ends of the column are hinge-supported assuming that the points of contra flexure in a structure are located at mid-height of the columns and beams. The beam tip is subjected to a vertical shear load in cyclic manner. Hanson and Connor [1] have first reported such experiments and demonstrated that joints with no hoops can lead to a poor load-displacement behavior of the sub-assembly. More specifically, diagonal cracks developed in the joint which finally caused a brittle joint shear (JS) failure with no yielding in the longitudinal reinforcing steel bars of the beam. The findings of this experimental campaign initiated a burst of activities on the non-linear behavior of beam-column joints both on experimental and numerical front, which corroborated the premature occurrence of the JS failure. Understandably, this is an undesirable failure mode in the seismic design philosophy due to its brittle nature and considerably lower amount of energy absorption compared to a flexural failure dominated by steel yielding.

In the literature, the vulnerability of the sub-assemblies has been investigated with respect to the applied non-seismic detailing. These can be joint cores with low amount of transverse reinforcement, inadequate anchorage of the beam longitudinal bars in the joint or lap splices in columns just above the joint, to name a few. One main parameter affecting the joint shear strength is the aspect ratio. The aspect ratio may be defined as the ratio between beam depth and column depth. By plotting the values of joint shear strengths of beam-column joints available in the literature over their aspect ratio, it can be inferred that with increasing aspect ratio, the joint shear strength decreases [2-4].

However, most studies have focused on 2D sub-asseblies, although in buildings, transverse beams and monolithically cast slabs are also present. As a result, it is important to consider 3D effects such as confinement of the transverse beams to the joint and slab contribution in order to realistically capture the joint shear behavior. This paper investigates the influence of the aspect ratio on 3D NSD exterior beam-column joints with transverse beams and slab. The investigation is performed within a numerical study with finite element (FE) code MASA developed at the University of Stuttgart.

2. EFFECT OF JOINT ASPECT RATIO

The joint shear strength is usually evaluated on the concept of the average plain stress plain strain approach. Design codes for new structures adopted this approach, where the average acting horizontal joints shear stress must be restricted within allowable limits to prevent joint shear failure. For the assessment of beam-column joints in existing non-seismically designed RC structures, proposed values for the critical joint shear stress can be found in FEMA 356 [5]. Another model based on the same approach is the principle tensile stress (p_t) method. The acting horizontal and vertical joint shear stresses are converted into principle stresses by employing the theory of Mohr´circle. For 2D exterior joints with deformed bars bent in the joint with a 90° hook, Priestley [6] suggested the values of $p_t = 0.29f'_c{}^{0,5}$ for first joint cracking and $p_t = 0.42f'_c{}^{0,5}$ for the ultimate joint strength, respectively. These values are recommended in the CEB240 [7].

However, it should be mentioned that the above design codes do not consider the aspect ratio (alpha) in the determination of the critical values for the joint shear strength. Wong [8] investigated 2D joints with three different aspect ratios (1, 1.5 and 2) and concluded that the joint shear strength decreases as the beam-column depth ratio increases. Same finding has been reported by Park [2] and Hassan [3] on corner joints with transverse beam and slab. To get more insight into the effect of the joint aspect ratio, a database of 50 2D exterior beam-column joints devoid of transverse reinforcement and with beam longitudinal bars bent in the joint is collected. The values of p_t evaluated according to Tsonos [9] are plotted over the aspect ratio (beam depth over column depth) in Fig. 1. The data base reveals that there is a trend of decrease in in the joint shear strength with increased aspect ratio. Sharma [10] proposed that p_t is inversely proportional to the aspect ratio, which is also included in the graph. It can be seen that CEB240 [7] overestimates the joint shear strength for higher values of alpha.

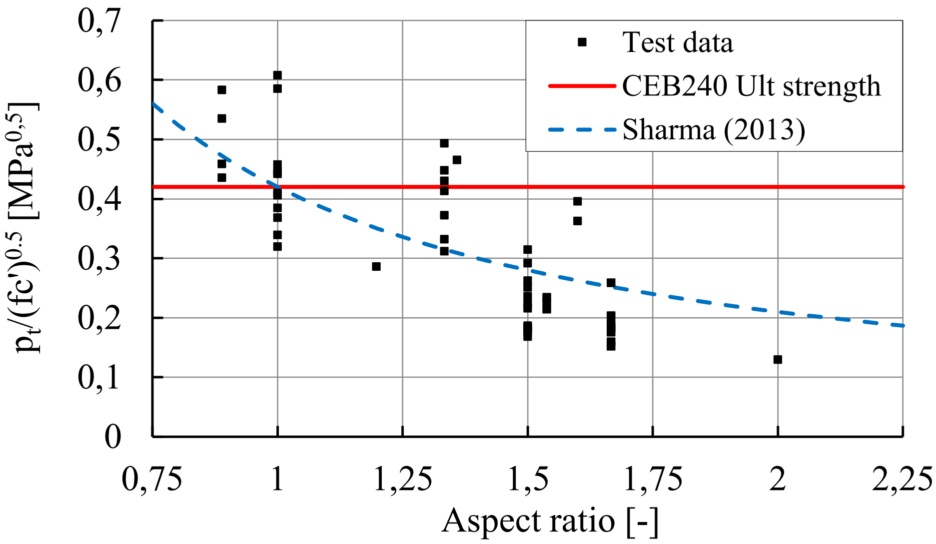

Fig. 1: Data base of exterior joints with bent in longitudinal beam bars

Fig. 2 explains the effect of higher aspect ratio on the joint shear strength. Subjecting the beam tip to a shear force in downward direction, the resulting internal bending forces in beam and column combine to generate a diagonal strut (S) in the joint panel.

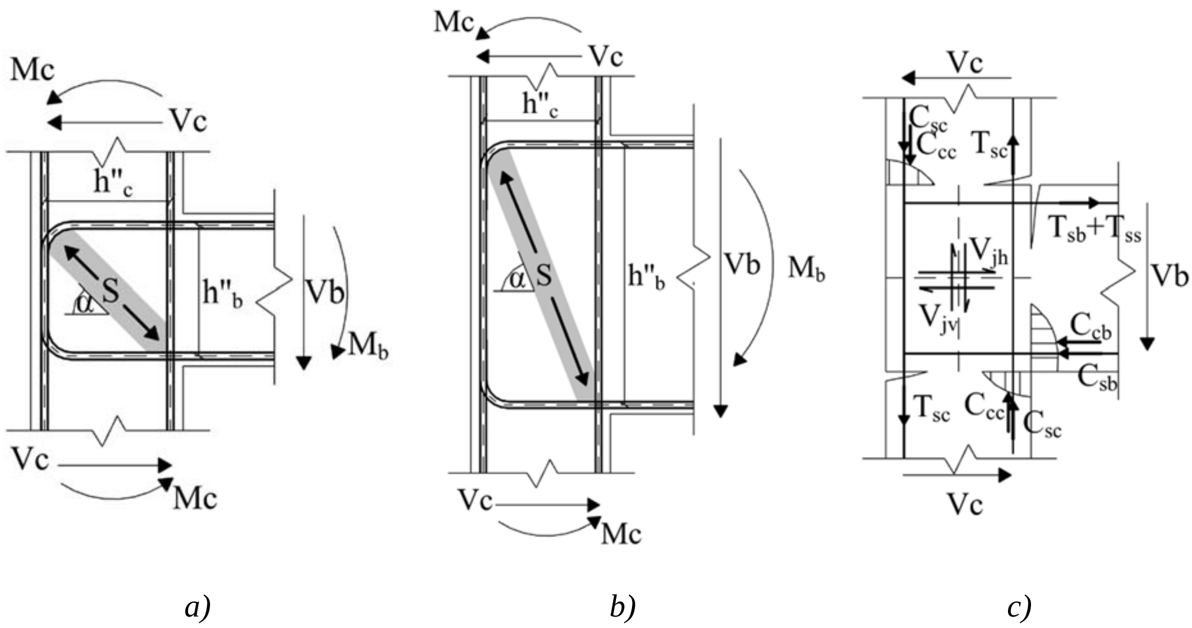

Fig. 2: Diagonal strut formation for a) alpha = 1, b) alpha =2 and c) horizontal and vertical joint shear of an exterior beam-column join with slab

The acting horizontal and vertical joint shear forces V_{jh} and V_{jv} are indicated in Fig. 2c. By forming horizontal equilibrium at mid-height of the joint panel, the horizontal joint shear force equals the difference between tensile force in beam longitudinal bars and column shear force. Because V_{jh} is resisted by the horizontal component of the diagonal strut S, it follows that the magnitude of compressive stresses in relatively steeper struts augment to resist the same V_{jh}. This fact is graphically represented in Fig. 2a and Fig. 2b. Moreover, it should be noted that after the onset of diagonal cracking in the joint, the strut stabilizes between the steel reinforcing bars. Thus, in the subsequent numerical study, the aspect ratio is defined as the ratio between the beam gender depth h''_b and column gender depth h''_c.

Another point to be mentioned is the presence of a slab. It is asserted that the tensile forces in the slab bars are resisted by joint shear [11], which are transferred through torsion of the transverse beam to the joint. Hence, for the calculation of V_{jh}, the tensile force of the slab bars T_{ss} adds to the tensile force of the longitudinal beam bars T_{sb} (see Fig. 2c). In this work, this fact is considered in the determination of p_t.

3. NUMERICAL STUDY

3.1 FE MODEL

The numerical simulations are performed using FE code MASA developed at the University of Stuttgart. The constitutive law of concrete is the microplane model with relaxed kinematic constraint [12]. Concrete is modeled using 8-node hexahedral elements with a mesh size between 20 mm and 30 mm. Reinforcing steel is modeled with two-node truss elements with an associated tri-linear uniaxial stress-strain law. To model bond between reinforcing steel and concrete, the bond link elements with zero thickness proposed by Lettow [13] are adopted.

3.2 INVESTIGATED BEAM-COLUMN JOINTS

The investigated beam-column joints in this study can be depicted in Fig. 3. The study aims at evaluating the trend of the principal tensile stress p_t with respect to different aspect ratios. In particular, it is examined how the trend of p_t for 3D joints deviates from the one for 2D joints due to the presence of transverse beams and slab. Note that the behavior of the joints is evaluated for the case when the beam is monotonically pushed down, e.g. when the slab is acting in tension. The transverse beam remains free and unloaded.

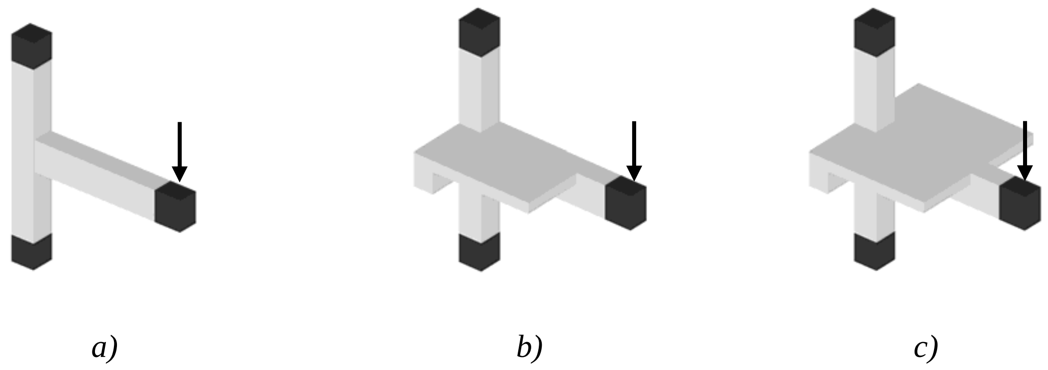

Fig. 3: Investigated exterior beam-column joints: a) 2D joint, b) corner joint and c) edge joint

The dimensions and reinforcement detailing of the beam-column joint sub-assembly for the case with 450 mm beam height is presented in Fig. 4. In all cases, the aspect ratio is varied by changing only the beam height, that is, the column cross section of 350 mm by 350 mm is always maintained. Given a concrete cover of 60 mm to center of the longitudinal steel bar in the beam and 50 mm in column, respectively, the aspect ratio in Fig. 4 equals 1.3.

In all simulations, a concrete cylinder compressive strength of 30 MPa is used. The reinforcing steel consists of standard BSt500 deformed bars. Both top and bottom longitudinal beam bars of the loaded beam are bent in with a 90° hook in the joint, where no transverse reinfocerment is present.

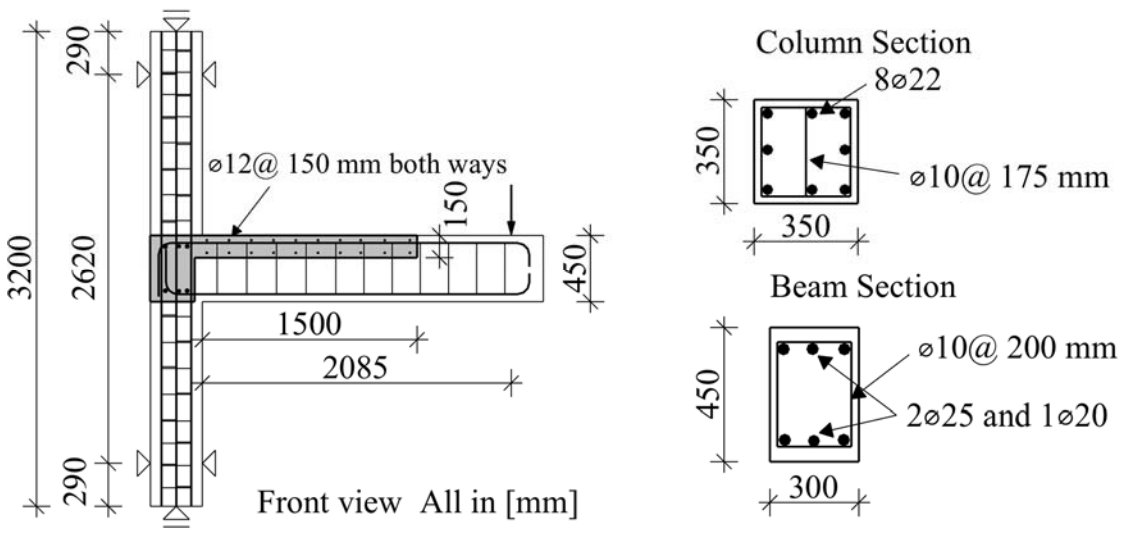

Fig. 4: Geometry and reinforcement detailing of the investigated beam-column joints

In the case of the corner joint, the longitudinal beam bars in the transverse beam are anchored with a 90° hook as well. In the case of the edge joint, the bars pass straight through the joint. As for the slab reinforcement, top slab bars terminate with a 90° hook while bottom slab bars are anchored straight.

The width of the sub-assembly including column width and slab width is 2050 mm for the edge joint and 1200 mm for the corner joint, respectively. An overview of the numerical simulations is given in Table 1.

Table 1: Overview of numerical simulations

Type of joint	**Aspect ratio**			
2D joint	0.92	1.32	1.72	2.32
Corner joint	0.92	1.32	1.72	2.32
Edge joint	0.92	1.32	1.72	2.32

3.3 CRACK FORMATION IN 3D BEAM-COLUMN JOINTS

To better understand the behavior of the investigated beam-column joints, the different stages of cracking are indicated in the numerical load-displacement curves. These consist of: flexural crack in the loaded beam for the 2D joint (B), flexural crack in slab for the 3D joints (S), flexural crack at onset of slab (O), joint shear crack (J), flexural crack in column (C) and torsional crack in transverse beam (T).

In Fig. 5, the different types of cracking along with their descriptions used in the following load-displacement curves are graphically shown for a corner joint at failure. The cracks are visualized by plotting the principal tensile strain ε_{11}, where the red color stands for the critical crack width of 0.3 mm. The sub-assembly undergoes a joint shear failure which is associated wide opening of the diagonal crack in the joint core. At failure, vertical cracks develop at the back side of the joint because of its horizontal dilatation. Furthermore, it can be seen that the slab subjects the transverse beam to torsion, which is manifested as helical cracks along the back side of the transverse beam.

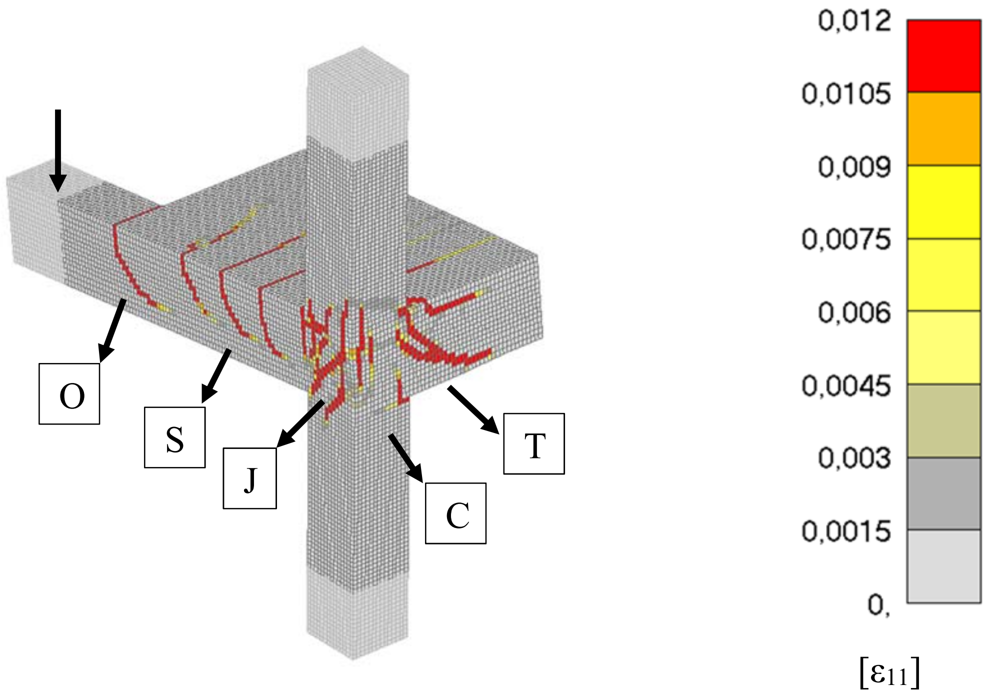

Fig. 5: Description of different cracking stages on corner joint at failure

3.4 BEAM-COLUMN JOINT WITHOUT TRANSVERSE BEAM AND SLAB (2D)

The load-displacement curves of the 2D beam-column joints with different aspect ratios are shown in Fig. 6. In the curves, the different states of cracking are also added. It can be nicely seen that with every crack formation, the curve exhibits a loss in stiffness. For all sub-assemblies, the first cracks are flexural ones in the beam. The curves reveal that the stiffness increases and amount of flexural cracks in the beam decreases for higher aspect ratios. Both findings are associated with the increased moment of inertia of the beam. Furthermore, the higher shear load on the beam results in higher shear loads on both column ends, which in turn induce flexural cracking in the column.

Concerning the joint shear behavior, the first joint shear crack develops at lower displacement and higher load for higher aspect ratios. It is of interest to note that the loss in stiffness for higher aspect ratios is more pronounced. This may be explained by the fact that the joint crack, which forms diagonally between the opposite corners of the joint panel, is longer for higher beam depth to column depth ratios. After the occurrence of the first joint crack, the regain in stiffness, that is, the slope of the curve, is greater for higher aspect ratios. Notwithstanding, the difference in the load level between the first joint crack and ultimate capacity diminishes, because a relatively higher aspect ratio adversely affects the strut stabilization. In the extreme case of an aspect ratio equal to 2.3, the load at first joint cracking approximately equals the ultimate load.

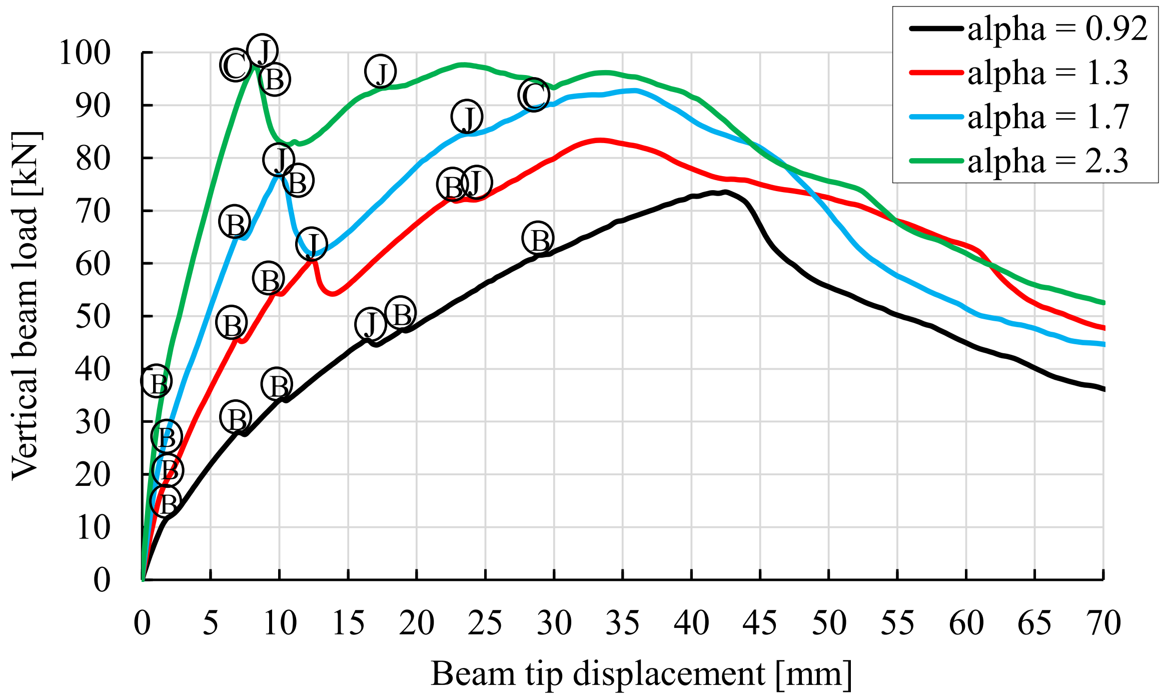

Fig. 6: Load-displacement curves of the 2D beam-column joints

The values of the principal tensile stresses p_t over the aspect ratio are presented in Fig. 7. The potential trend of the numerical results is also added. They show good agreement with the model proposed by Sharma [10].

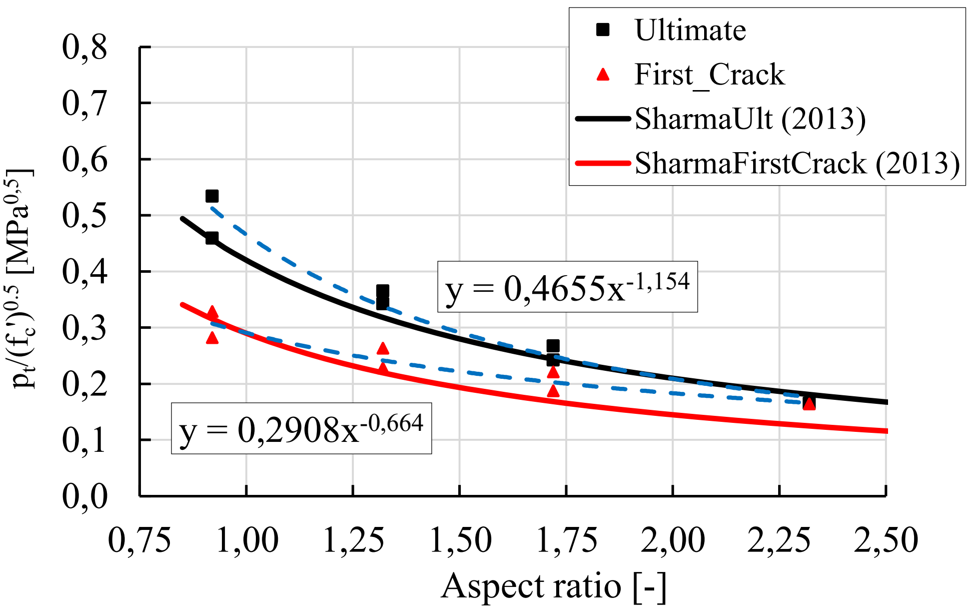

Fig. 7: p_t versus alpha of the 2D beam-column joints

Similar to the vertical beam load, the values of p_t for first joint cracking and ultimate joint strength draw near with increasing aspect ratios. All investigated 2D joints undergo a joint-shear failure.

3.5 CORNER BEAM-COLUMN JOINTS

Fig. 8 presents the load-displacement curves of the corner beam-column joints with transverse beam and slab for different aspect ratios. It should be noted that the transverse beam of the sub-assembly has the same cross section as the loaded beam. Hence, the torsional resistance of the transverse beam augments with an increase in the aspect ratio.

Inspection of the curves reveals that more cracks form in 3D beam-column joints compared to 2D joints. On the one hand, the slab subjects the transverse beam to torsion, which results to the development of torsional cracks, as it can be seen in Fig. 5. These cracks originate from the column and helically propagate along the back side of the transverse beam. It can be further seen that with increasing aspect ratio, the formation of the torsional crack occurs at lower beam tip displacements and higher loads. On the other hand, the loads in the corner joint reach higher values compared to the 2D joint, which leads to more flexural cracks in slab and column.

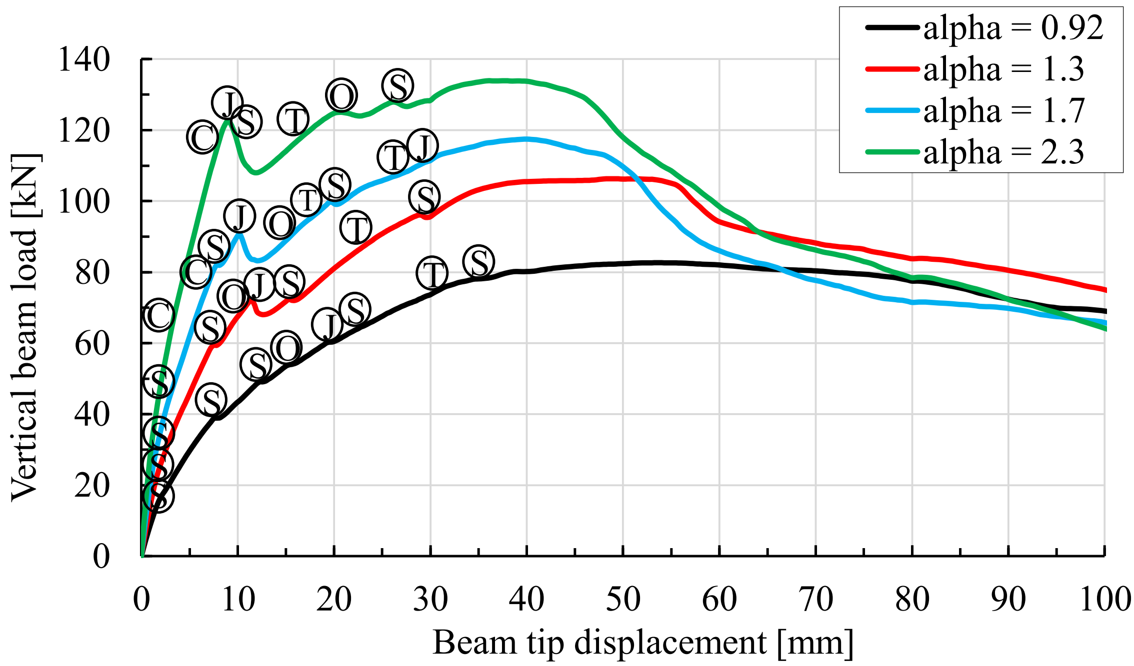

Fig. 8: Load-displacement curves of the corner beam-column joints

The reason for the higher load values can be explained by the slab contribution in the load-transfer and the induced confinement of the transverse beam to the joint. It is also of interest to note that the regain in stiffness after the first joint crack is not as high as in the 2D joints. This is particularly true for the aspect ratios of 1.7 and 2.3. This finding may be due to the fact that the tensile stresses in the slab bars adversely affect the strut stabilization since they add to the tensile forces which have to be resisted by joint shear.

The values of the principal tensile stresses p_t of the ultimate joint shear strength and of the first joint crack along with their potential trend are depicted in Fig. 9. It can be inferred that the critical values of p_t are higher compared to the 2D joints due to 3D effects such as slab contribution and confinement of transverse beam and slab to the joint. However, the degradation of the trend is rather similar.

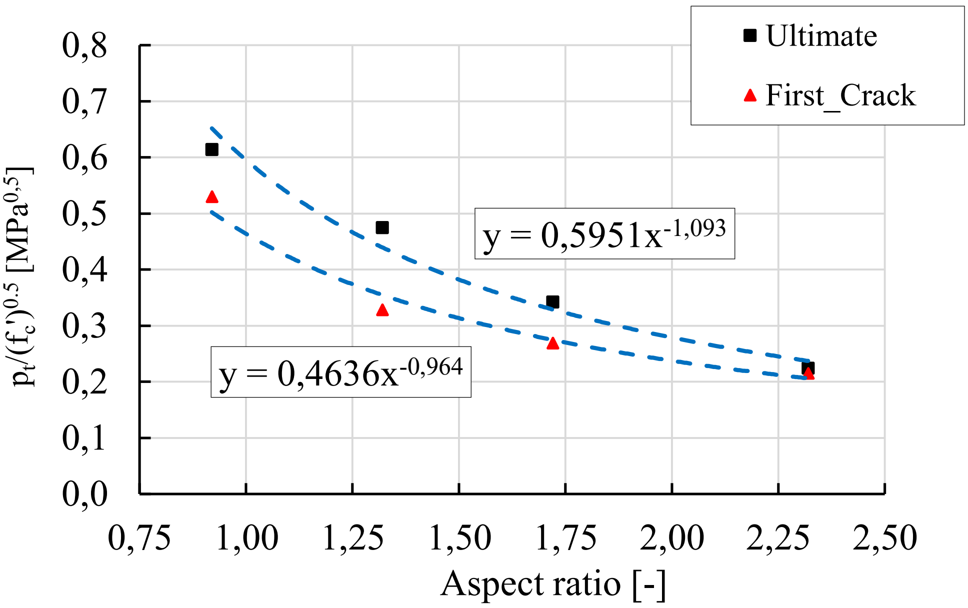

Fig. 9: p_t versus alpha of the corner beam-column joints

3.6 EDGE BEAM-COLUMN JOINTS

Fig. 10 shows the load-displacement curves of the edge beam-column joints. Contrary to the corner joint, the edge joint with alpha equal to 0.92 fails due to the torsional failure of the transverse beam. On closer scrutiny, the torsional crack forms before joint cracking occurs. This means that the ultimate joint shear strength has not been reached due to the preceding failure of the transverse beam. Still, the peak load of the edge joint is higher than the one of the corner joint, which means that the ultimate joint shear strength of the edge is also higher.

As for the other aspect ratios, the first joint crack occurs first and the loss in the load-carrying capacity of the sub-assembly is caused by a joint shear failure. The regains in stiffness after the first joint crack further drops compared to the corner joints, because in the edge joints the slab contributes more and consequently leads to an enhanced disturbance of the strut stabilzation.

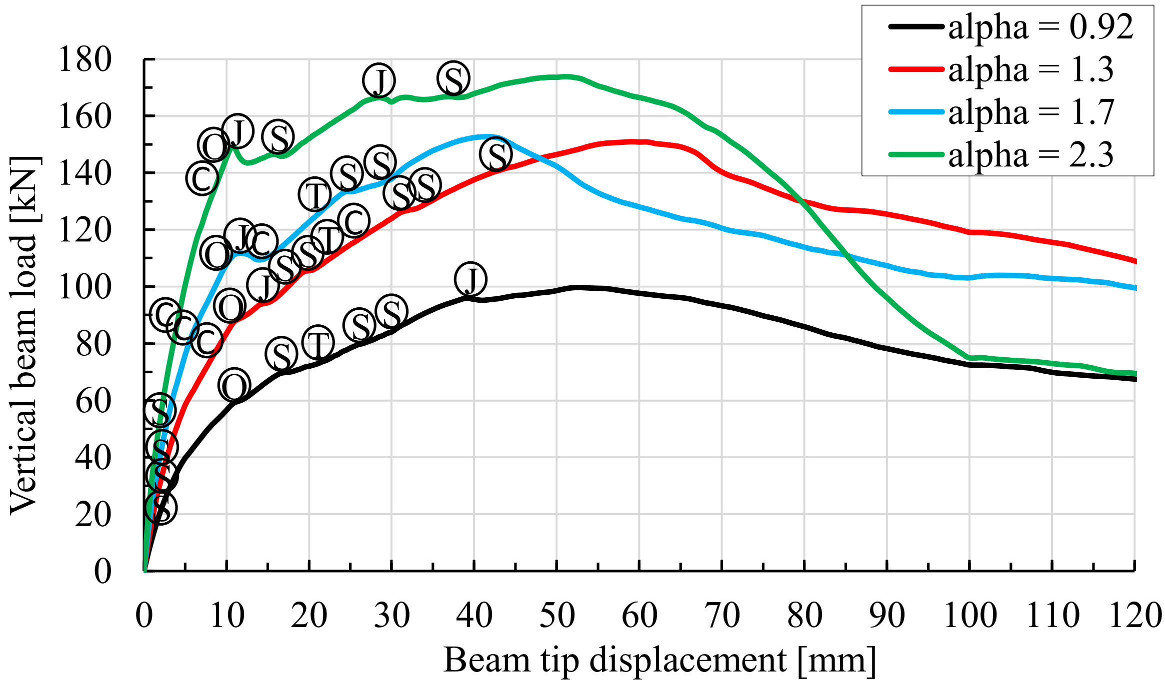

Fig. 10: Load-displacement curves of the edge beam-column joints

The attained values of the principal tensile stresses p_t for the investigated edge joints are illustrated in Fig. 11. Note that due to the preceding torsional failure of the transverse beam for the case of alpha equal to 0.92, only the p_t at first joint cracking is incorporated in the trend. The results show that the degradation of the ultimate joint shear strength is stronger compared to the 2D and corner joints.

It can be deduced from the values that the effect of the slab and transverse beam on the joint shear behavior is most significant for the edge joints. Now, a transverse beam is framing into the joint from two sides and the slab contribution increased. For instance, the critical principal tensile stress for the first joint crack and aspeact ratio equal to 1 suggested by Priestley is $0.29f'_c{}^{0,5}$,whereas for the corner and edge joint, the value increases up to $0.46f'_c{}^{0,5}$ and $0.64f'_c{}^{0,5}$, respectively.

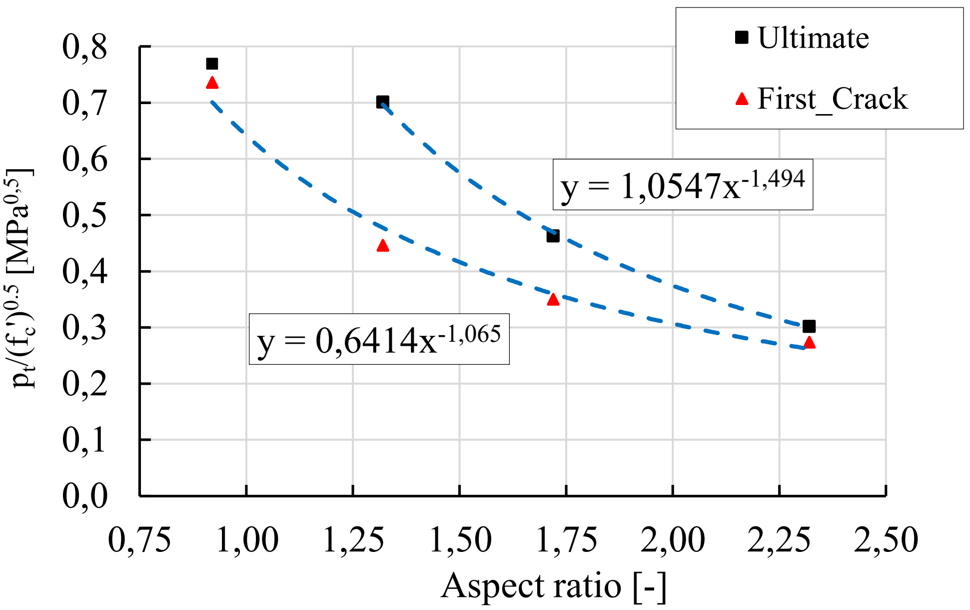

Fig. 11: p_t versus alpha of the edge beam-column joints

4. CONCLUSIONS

The effect of the joint aspect ratio on the joints shear strength of 3D beam-column joints has been investigated in the framework of a finite element study. It has been shown that the critical values of principal tensile stresses of 3D joints differ from the ones proposed for 2D joints in the literature. This is due to the slab participation and the confinement induced to the joint by the transverse beam and slab. The demand on the joint shear resistance increases due to the additional tensile stresses in the slab bars, which are transferred to the joint through torsion of the transverse beam. In one example, it has been shown that for relatively low torsional resistance of the transverse beam, which is often the case for low aspect ratios, the ultimate joint shear resistance may not be reached due to a preceding torsional failure of the transverse beam.

Similar to the 2D joints, the joint shear resistance of the investigated 3D joints decreases with an increase in the aspect ratio. By evaluating the potential trend line of the attained p_t values, it has been found that the degradation of the 2D joints and corner joints is quite similar, whereas the degradation of the ultimate joint shear capacity is relatively stronger in the case of the edge joints.

REFERENCES

[1] HANSON, N.W., CONNOR, H.W.: *Seismic resistance of reinforced concrete beam-column joints*. Journal of the Structural Division Proceedings of the American Society of Civil Engineers, 1967

[2] PARK, S.: *Experimental and analytical studies on old reinforced concrete buildings with seismically vulnerable beam-column joints. PhD Thesis.* University of California, Berkeley, 2010

[3] HASSAN, W.M.: *Analytical and experimental assessment of seismic vulnerability of beam-column joints without transverse reinforcement in concrete buildings. PhD Thesis.* University of California, Berkeley, 2011

[4] SHARMA, A., HOFMANN, J.: *Modeling parameters for beam-column joints in seismic performance assessment of structures – a new proposal.* Fib Symposium, Capetown, 2016

[5] FEDERAL EMERGENCY MANAGEMENT AGENCY: *Prestandard and commentary for the seismic rehabilitation of buildings.* FEMA, Washington, D.C., 2000

[6] PRIESTLEY, M.J.N.: *Displacement based seismic assessment of reinforced concrete buildings.* Journal of earthquake engineering, 1997

[7] COMITE EURO-INTERNATIONAL DU BETON: *Seismic design of reinforced concrete structures for controlled inelastic response.* Thomas Telford Ltd, 1998

[8] WONG, H.F., KUANG, J.S.: *Effects of beam-column depth ratio on joint seismic behavior.* Structures and Buildings, 2008, 161 (2), pp. 91–101

[9] TSONOS, A.G.: *Cyclic load behavior of reinforced concrete beam-column subassemblages of modern structures.* ACI Structural journal, 2007, 104 (4), pp. 468-478

[10] SHARMA, A.: *Seismic Behavior and Retrofitting of RC Frame Structures with Emphasis on Beam-Column Joints – Experiments and Numerical Modeling. PhD Thesis.* University of Stuttgart, 2013

[11] PANTAZOPOULOU, S., FRENCH, C.: *Slab Participation in Practical Design of R.C. Frames.* ACI Structural journal, 2001, 98 (4), pp. 479-489

[12] OZBOLT, J., LI, Y., KOZAR, I.: *Microplane model for concrete with relaxed kinematic constraint.* International Journal of Solids and Structures, 2001, 38 (16), pp. 2683-2711

[13] LETTOW, S.: *Ein Verbundelement für nichtlineare Finite Elemente Analysen – Anwendung auf Übergreifungsstöße. PhD Thesis.* University of Stuttgart, 2007