POST-INSTALLED ANCHORS IN CORNER CONFIGURATION – NUMERICAL INVESTIGATION

NACHTRÄGLICH MONTIERTE BEFESTIGUNGSMITTEL IN RÄUMLICHER ECK-KONFIGURATION – NUMERISCHE UNTERSUCHUNG

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SUMMARY

Anchorages are often required at the corners of frame structures. For example, when diagonal steel bracings are attached to the corner of a reinforced concrete frame to strengthen it against seismic actions. However, there are no guidelines or standards available which provide a design solution for such a corner configuration. To this end, a numerical analysis is performed to investigate the geometrical influences on the breakout behaviour of such a corner connection. In particular the load-displacement behaviour is studied and how it is affected by the strength of the concrete. Furthermore, this work investigates how the behaviour in the corner differs from the behaviour when installed in a narrow single member without the influence of the second perpendicular member.

ZUSAMMENFASSUNG

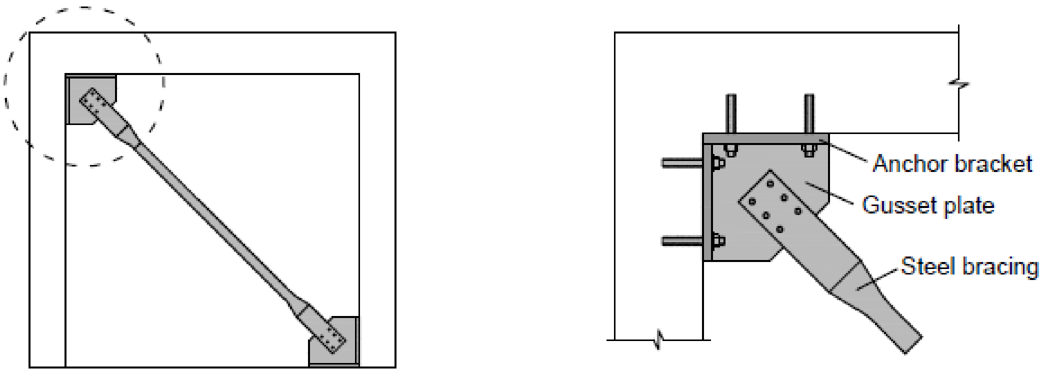
Werden Stahlverstrebungen eingesetzt, um ein Stahlbeton-Rahmentragwerk gegen Erdbebenbelastungen zu verstärken, bieten nachträgliche montierbare Befestigungsmittel eine minimal-invasive und praktikable Lösung, um die Stahlverstrebungen in den Ecken des Rahmentragwerks zu befestigen. Ein Problem, das bei der Bemessung einer solchen räumlichen Ankerkonfiguration in der Ecke unweigerlich auftritt, ist das Fehlen von Konstruktionsregeln oder Bemessungsverfahren. Aus diesem Grund wird in dieser Arbeite ein solcher Eck-Anschluss numerisch untersucht. Dabei liegt der Fokus dieser Arbeit auf dem Einfluss der Betonfestigkeit und dem Einfluss der Betonecke auf das Last-Verschiebungsverhalten des Anschlusses.

1. INTRODUCTION

Strengthening of reinforced concrete (RC) frame structures by means of diagonal steel bracings is a popular solution to increase the lateral resistance against earthquake loading. In doing so the load-transfer mechanism of the structure is altered from a moment resisting frame to a predominantly truss-mechanism. This alteration of the load-transfer mechanism results in a marked improvement of the global characteristics of the structure, such as the lateral capacity, the global stiffness of the structure or its ductile behaviour as shown in Abou-Elfath and Ghobarah [1] and Badoux and Jirsa [2]. The effectiveness of the strengthening solution is thereby highly related to the performance of the connection between the new structural elements and the existing structure as shown in Mahrenholtz et al. [3].

A common approach is to indirectly connect the steel bracings to the RC frame by means of an additional steel frame which, due to a lack of design guidelines, needs to be fastened to the RC frame along the complete perimeter using post-installed anchors or reinforcing bars. It is apparent that such an approach is rather invasive, costly, and associated with an elaborate installation. Direct fastening solutions using steel-jackets, bolted-thorough connections or external rods have proven to be an efficient and less invasive alternative [4-7]. In this work a direct connection using post-installed anchors is investigated numerically. The main benefits of using post-installed anchors are their low invasiveness, their practicability, and an easy and fast installation process.

In case of strengthening solutions using diagonal steel bracings, the connection between the new structural element and the existing structure is placed in the corner of the RC frame as indicated in Fig. 1 (a). In such a connection, the steel bracing is attached to a gusset plate which is welded to an L-shaped anchor bracket. The anchor bracket is in turn connected to the RC frame using post-installed anchors. Fig. 1 (b) schematically depicts such a connection. The anchor bracket and the anchors can also be viewed, for practical convenience, as two groups of anchors arranged perpendicular to each other. The major issue arising when using post-installed anchors in such a spatial configuration is the lack of design recommendations as such configurations are not covered in current design guidelines or standards. It should be noted that in case of such a configuration concrete breakout failure is of particular interest. Other potential failure modes such as steel failure or pull-out failure are, in contrast to concrete breakout failure, characterized by a rather ductile load-displacement behaviour, and the vicinity of free edges or neighbouring anchors has no influence on the ultimate group capacity. On the other hand, the probability of concrete breakout failure being the critical failure mode is increased due to the presence of close edges in beams and columns as there is less concrete available to resist the loads on the connection. To this end, in Stehle and Sharma [8] a numerical analysis was performed where the focus was laid on the geometrical influences on the breakout behaviour of such a corner configuration. Therefore, the concrete specimen was modelled in such a way that effects like bending of the RC members or the frame action effect on the gusset plate [9], which would affect the behaviour in real applications, were hindered. Two objectives were investigated in the numerical study, the influence of varying embedment depths and how the load-displacement behaviour of the connection changes when only one of the perpendicular anchor groups is attached to the corner (partly attached connection). It was found that with increasing embedment depth, the load-displacement behaviour of the complete connections becomes stiffer in the ascending branch while the behaviour after reaching the ultimate load becomes more brittle. The comparison between fully and partly attached connection led to the result that the ultimate capacity and the stiffness of the partly attached connection is around half the respective values of the fully attached connection. Nevertheless, the beneficial effect which the corner had on the partly attached connection was apparent from a distinct load plateau after reaching the ultimate capacity.



(a) (b)

Fig. 1: RC frame structure strengthened by steel bracing (a) complete structure and (b) connection detail

The numerical study presented in this work is an extension or addition to the study conducted by Stehle and Sharma [8] and is intended to advance the understanding of the breakout behaviour of this type of spatial anchor configuration. Therefore, two major objectives are investigated. First, a numerical parametric study is conducted in which the effect of varying concrete strength is investigated. To this end, the same numerical model is used as in [8], where the connection is fully attached to the concrete specimen by means of bonded anchors with an embedment depth of h_{ef} = 110 mm. The second objective is to further investigate, to which extend the installation in a corner influences the behaviour of the connection. Therefore, the case is simulated where the connection is solely fastened to one narrow concrete member (beam or column) while the second perpendicular member is not modelled. This basically means that one anchor group is installed in a single narrow member (two close edges) and loaded with an angle of 45°. The results of these simulations are compared to the previously investigated partly attached connections in [8].

2. NUMERICAL MODELLING APPROACH

2.1 Numerical model

The numerical analysis in this work is performed using the 3D finite element software MASA (Macroscopic Space Analysis) developed at the Institute of Construction Materials at the University of Stuttgart. In MASA, the constitutive law for concrete is the microplane model with relaxed kinematic constraint proposed by [10], where a smeared crack approach is applied to simulate the damage and fracture phenomena. In MASA, the crack band method [11] is used as a so-called localization limiter, which ensures the mesh-independency of the numerical results. For pre- and post-processing, the software FEMAP (Siemens) is used. Concrete is modelled using 4-node tetrahedral elements, the steel parts such as the gusset plate, the anchor bracket, and the anchor rods are modelled using 8-node hexahedral elements. The bond between the anchor rods and the surrounding concrete is simulated using 2-node bar elements which are only capable of transferring compression and shear (bond) forces. The discretization of the bond stress-slip behaviour is given in Fig. 2. Similarly, compression-only 2-node bar elements are used to simulate the contact between the anchor bracket and the concrete surface. The described modelling approach has been successfully applied in previous numerical studies aiming on the investigation of bonded anchors installed in concrete or the investigation of RC structures [12-14].

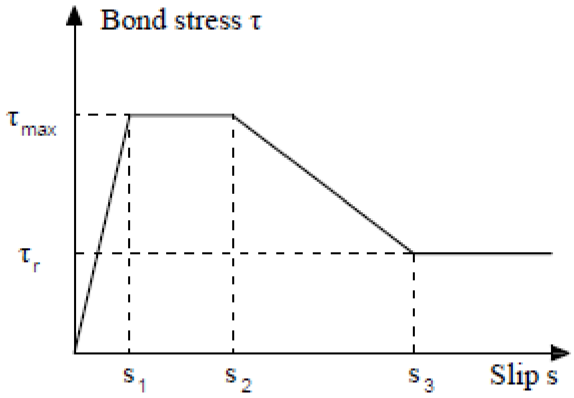
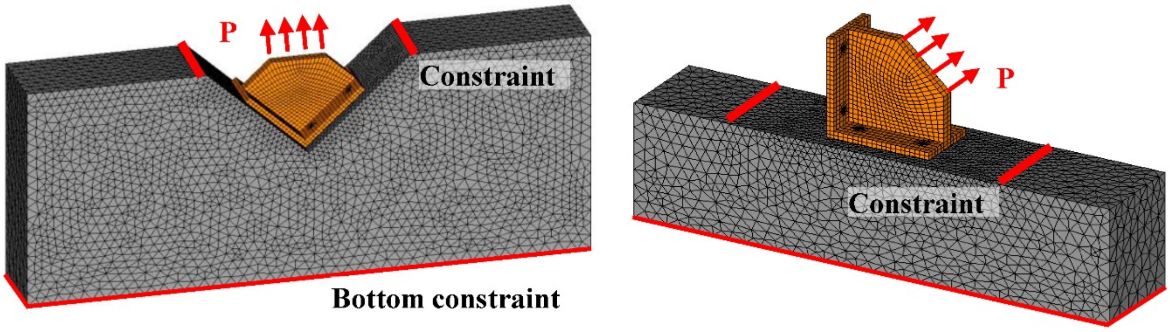


Fig. 2: Discretization of bond stress-slip behaviour of the 2-node bar elements used to simulate the bond between steel and concrete for the bonded anchors

2.2 Description of the investigated specimen

As mentioned above, the main emphasis is on the concrete breakout behaviour of the corner configuration shown in Fig. 1 and the geometrical influence thereon. To this end, the concrete specimen was designed to exclude additional effects, such as bending of the RC members, which would have made the assessment of the mere behaviour of this geometrical configuration difficult. Note that the numerical model in this study is the same model which was used in [8]. The discretization of the concrete specimen and the connection element is shown in Fig. 3 (a). The connection comprises a gusset plate, an anchor bracket and eight bonded anchors. The anchor rods have a diameter of d = 16 mm and are embedded in the concrete with an embedment depth of h_{ef} = 110 mm. The geometry of the concrete specimen, the dimensions of the steel elements and the geometrical arrangement of the anchors (anchor spacing and edge distance) are provided in Fig. 4. Note that the concrete specimen has no reinforcement. Bending and sliding of the concrete specimen is hindered by directly applying constraints onto the bottom nodes of the specimen as indicated in Fig. 3 (a). Similarly, constraints are applied onto the nodes on the edge of the triangular recess. As can be seen from Fig. 4, this leads to a clear distance of $2h_{ef}$ between the constraints on the upper side of the concrete specimen and the outer most anchors of the connection. This distance was chosen based on the stipulated unconfined test setup according to EOTA TR 048 [15], which allows an unrestricted formation of the concrete cone breakout body in case of static pull-out tests. The connection is loaded in displacement control by incrementally increasing the displacement applied on the upper surface of the gusset plate as shown in Fig. 3 (a). In this way, the ultimate capacity of the connection is generally reached within 50 – 60 steps. To calculate the total force acting on the connection the individual forces on the loaded nodes in the direction of loading are added up. To investigate the breakout and load-displacement behaviour of the connection for different concrete strength classes, the concrete cylinder compressive strength was varied from 20 – 50 N/mm² according to the strength classes provided in EN 1992-1-1 [16]. Steel elements were modelled assuming linear-elastic material behaviour where Young's Modulus is E_s = 200000 N/mm² and Poisson's ratio is μ_s = 0.33.



(a) (b)

Fig. 3: (a) FE discretization of the complete model used for the parametric study on the influence of concrete strength and (b) FE discretization of the connection element installed in a narrow concrete member

In Stehle and Sharma [8] two cases were investigated. In the first case the connection was fully attached to the simulated corner. Applied to real applications, this arrangement requires that one group be fastened to the beam and the second group to the column. In the second case only one of the two perpendicular anchor groups was attached to a concrete member. Nevertheless, also in this case the second perpendicular concrete member inevitably influences the load-displacement and breakout behaviour of the connection, even if the connection is not directly attached to it. In order to investigate the extent to which the presence of a second perpendicular concrete member has an influence on the connection, the case is investigated where the connection is installed in a single narrow concrete member. The corresponding numerical model is shown in Fig. 3 (b). The simulated concrete specimen has a length of L = 1200 mm, a width of W = 240 mm and a height of H = 300 mm. The dimensions of the steel elements and the geometrical arrangement of the anchors remains unchanged. The constraints on the upper surface of the concrete specimen are placed on both sides of the connection at a clear distance of >$2h_{ef}$ from the outermost anchors. The load is applied in displacement control at an angle of 45° as indicated in Fig. 3 (b). To allow a comparison with the results obtained in [8], three simulations were performed with three different embedment depths, namely $h_{ef,1}$ = 80 mm, $h_{ef,2}$ = 110 mm and $h_{ef,3}$ = 150 mm. For these three simulations, the mean cylinder compressive strength of concrete is kept constant as f_c = 20 N/mm². The material of the gusset plate and anchor bracket are considered linear elastic. For the anchor rods, non-linear material behaviour was considered using von Mises plasticity criteria, where the yield stress is taken as f_y = 640 N/mm² and the ultimate strength as f_u = 800 N/mm².

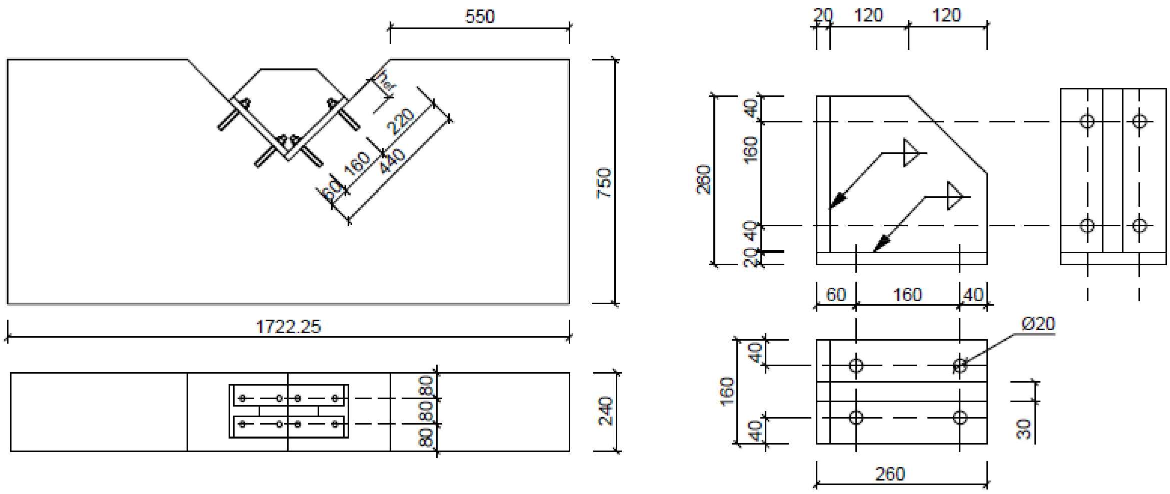


Fig. 4: Dimensions of the concrete specimen (left) and the connection element (right). (Note: All dimensions are in mm)

3. NUMERICAL RESULTS

In this section the numerical results are presented. Table 1 contains an overview of the numerical program and the numerical results in terms of loads and displacements. Note that in case of the fully attached connection, it was observed that the load-displacement behaviour is characterized by a first peak after which the connection loses parts of its load-bearing capacity followed by a second ascending branch where the connection regains strength until it reaches its ultimate capacity [8]. In this regard, P_1 and s_1 correspond to first peak (first drop in the load) while P_u and s_u refer to the absolute peak where the ultimate capacity is obtained. The first peak is observed only in the case of fully attached specimen and is attributed to the stabilization of the compression struts from the two orthogonal anchor groups of the anchorage. The load-displacement curves of the individual simulations are presented where relevant for the discussion. The simulations are denoted as follows. The first two letters are the same for all simulations and refer to Bracket Configuration. The first number (80, 110, and 150) identifies the embedment depth of the bonded anchors (in mm) in the respective simulation. The last two letters identify whether the connection is fully attached (FA) to the corner as shown in Fig. 3 (a) or whether it is installed in a single narrow concrete member (NM) as shown in Fig. 3 (b).

Table 1: Numerical program and summary of the numerical results

ID	h_{ef} (1) (mm)	f_c (2) (N/mm²)	P_1 (3) (kN)	s_1 (4) (mm)	P_u (5) (kN)	s_u (6) (mm)
BC-110-FA-1	110	20	243.0	0.27	291.3	0.88
BC-110-FA-2	110	25	296.1	0.30	363.3	0.88
BC-110-FA-3	110	30	339.9	0.33	424.7	0.88
BC-110-FA-4	110	35	380.2	0.35	471.0	0.95
BC-110-FA-5	110	40	416.1	0.37	501.4	0.86
BC-110-FA-6	110	45	446.0	0.38	535.1	0.92
BC-110-FA-7	110	50	472.3	0.40	562.0	0.88
BC-80-NM	80	20	-	-	90.3	0.18
BC-110-NM	110	20	-	-	110.6	0.21
BC-150-NM	150	20	-	-	133.3	0.24

(1) Effective embedment depth
(2) Cylinder concrete compressive strength
(3) Load at first peak
(4) Displacement at first peak
(5) Ultimate load
(6) Displacement at ultimate load

3.1 Influence of concrete strength

Fig. 5 presents the load-displacement curves obtained from the numerical analysis for the case where the connection is fully fastened to the corner by means of bonded anchors with an embedment depth of 110 mm. Each curve represents the analysis of a different strength class for the base material, thereby varying the concrete compressive strength from 20 N/mm² to 50 N/mm². The results in terms of loads and displacements are also summarized in Table 1. Besides the fact that, as would be expected, the ultimate capacity of the connection is higher at higher strength classes, the load-displacement behaviour of the connection also changes as the strength increases. This is evident from the post-peak behaviour which becomes more brittle.

In the beginning of the ascending branch, the load increases until the first peak is reached. It can be seen that the initial stiffness of the connection is rather similar regardless of the concrete strength class. However, the secant stiffness at first peak already increases at higher strength classes. This result is even more pronounced considering the behaviour of the connection as it regains its strength after the load has dropped to a local minimum. In this second face of ascending load, the stiffness of the connection is again higher at higher strength classes. At the same time, the secant stiffness at ultimate load also increases. Besides the stiffer behaviour of the connection in the ascending branch, higher concrete strength classes result in a more brittle post-peak behaviour. As can be seen in Fig. 5, in case of lower strength classes, the load-displacement curve shows a distinct load plateau with a gradual decrease in the load. With higher strength class, this plateau is getting smaller, and the descending branch becomes significantly steeper. A similar behaviour with regards to the ascending and descending branch of the load-displacement curve was observed when the embedment depth of the anchors was increased as shown in [8].

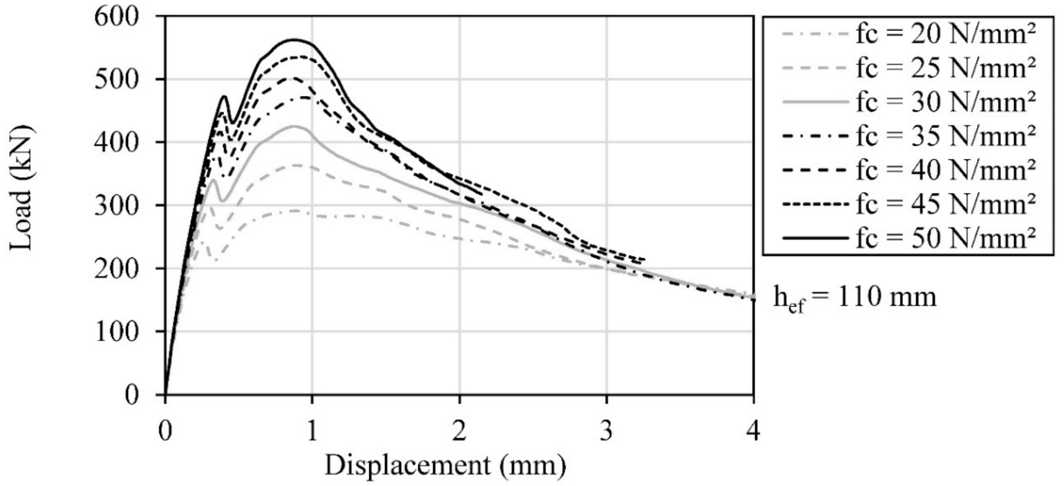


Fig. 5: Load-displacement curves obtained from the numerical analysis of the fully attached connection for varying concrete strength classes

3.2 Connection installed in single concrete member

In Table 1 the ultimate capacities and the corresponding displacements at ultimate load for the connection shown in Fig. 3 (b) are presented. Fig. 6 shows the corresponding load-displacement curves along with the curves obtained from the simulations where the connection was partly attached (PA) to the corner [8]. The dotted lines represent the numerical results corresponding to the partly attached connection and the solid lines represent the numerical results corresponding to the connection installed in a single narrow member. As can be seen, the load-displacement behaviour of the connection installed in a narrow member is characterized by a single peak at ultimate load and a relatively steep drop of load thereafter. Thereby, the ultimate capacity of narrow members is on an average around 10% lower compared to the load obtained at the first peak in the corresponding partly attached simulations in [8]. However, the secant stiffness at peak load matches well with the secant stiffness obtained at the first peak in the partly attached simulations. The comparison of the numerical results suggests that the regain in strength observed in the partly attached simulations in [8] is in fact a result of the second perpendicular concrete member. This is also evident from the failure mechanism observed in the present study where first the two anchors closest to the corner of the anchor bracket fail by an inclined crack towards the concrete surface. While the formation of this crack results in the failure of the connection in a single narrow member, the compressive strut is able to stabilize again due to the second concrete member and the joint region in case of the partly attached simulation. This stabilization of the compressive strut results in the regaining of strength up to the ultimate load, which is around 30% - 40% higher than the ultimate capacity obtained when installed in a single concrete member.

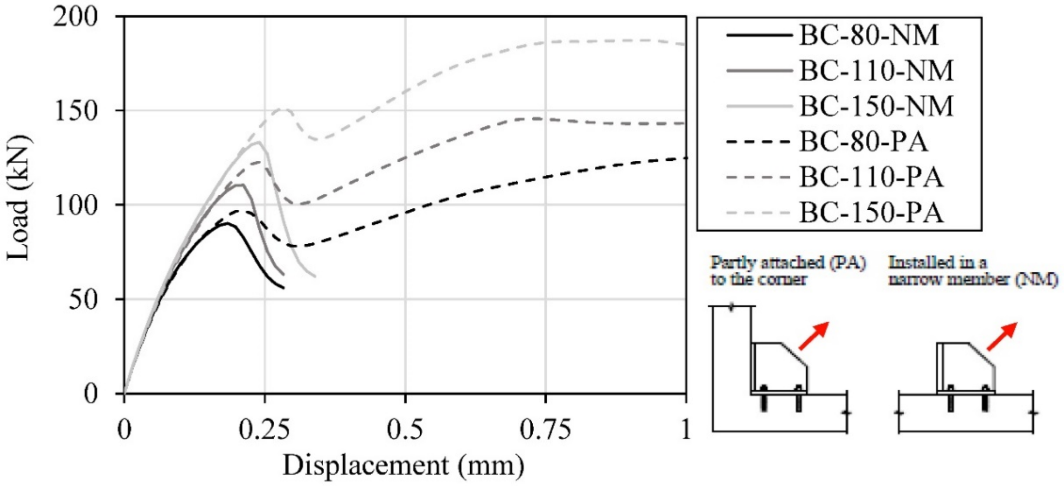


Fig. 6: Load-displacement curves obtained from the numerical analysis of the connection installed in a narrow concrete member (NM) and when partly attached to the corner (PA)

4. CONCLUSION

In this work a numerical investigation on the geometrical effect of a corner configuration was conducted. The investigated connection comprises a gusset plate and an anchor bracket which are connected to the concrete corner by means of post-installed bonded anchors. A parametric study was performed to investigate the influence of different concrete strength classes on the behaviour of the connection. It was found that besides an increased capacity, higher concrete strength classes resulted in a significantly stiffer behaviour in the ascending branch of the load-displacement curve while at the same time the post-peak behaviour became more brittle.

The second objective of this work was the investigation of the case where the connection was solely attached to a single concrete member and the comparison to the case where the connection was partly attached to the concrete corner. The comparison of the load-displacement behaviour clearly showed the beneficial effect that arises when such a connection is installed in the corner of a concrete member. The inclined loading of the connection results in an uneven distribution of the resulting tension load on the anchors. When installed in a narrow concrete member, this in turn causes the two anchors closest to the corner of the anchor bracket to fail first. Thereby the failure is indicated by an inclined crack propagation towards the concrete surface. When installed in the corner however, the compression strut and the accompanying crack growth is stabilized due to the beneficial effect of the second perpendicular concrete member and the joint. This results in the connection regaining its strength after a short drop in the load. These numerical findings will be verified by the tests to be conducted soon by the authors.

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