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AN INCURSION ON PUNCHING OF REINFORCED CONCRETE FLAT SLABS

BY

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Abstract. Starting from the early 60s continuous studies have been made regarding punching of concrete flat slabs. The evolution of technology and calculus systems influenced this engineering branch. Nowadays is possible to account in structural analysis all the non-linear behaviour of reinforced and prestressed concrete and to get the most close structural response in comparison with the real behaviour. As a controversy matter, several tests and theories have been developed. Nowadays researchers try to find the most accurate and economic formula for punching. This paper purpose is to make a survey on punching classical model and related nonlinear concrete behaviour regarded to this issue.

Key Words: punching; flat-slab-column connection; concrete behaviour; code design comparison.

1. Introduction

Since 1956, a serious bench of tests, over 400, have been gained due to the several numerical investigations and experimental tests. One of the most important center, where the most comprehensive theories and best experimental results were gained is the Departament of Structural Engineering from Stockholm Polytechnic under the surveillance of Prof. Herik Nylander and Prof. Sven Kinnunen. The most representative researches that studied this problem are: Kinnunen and Nylander, Moe, Braestrup and Nielsen, Menterey, Shehata, Bazant and Cao, Georgopoulus, Broms, Bortolotii, Alexander/Simmonds. Their models are presented in FIB Bulletin 12.

Even if punching was not a very important discussion topic in FIB taskgroups. On the background of the economical growth and the necessity of many more administrative buildings this theme is back on the list of "priorities". At this moment a coherent and accurate formulation for punching is sought.

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2. Composite Material Particular Behaviour

Structural design methods do not count at all on tensile strength of concrete. This way of thinking do not shows the real behaviour at limit state of the composite material: plain concrete, reinforced, partially of fully prestressed concrete. For all this type of materials constitued from different fractions of different stiffness tensile strength is a very important aspect because it makes the connections between constitutive particles.

When the member is in compression, the stiffer particles carry the loads creating a solid matrix of cement which, actually, indicate the compressive strength of the material. It should be mentioned that cement is the material that limits the bearing capacities of concrete.

It is interesting to observe with a microscope what really happens in concrete when loads are applied. Cement paste is hydrated, in its consistence there are harder crystals of amorphous porous mass (heterogeneous mass). It can be expected that under tension the amorphous paste and the reinforcing crystals starts to develop. Bond becomes friction based until the crystals loose its grip and cracks appear. Such insights lead to fracture mechanics, which explain the size effect. It is extremelly important to understand the shear transfer mechanisms. Related to that, it has been evidenced that the dowel effect and aggregate interlock influence heavily the reinforced concrete behaviour and flow of forces. Some of the most important particularities which affect the behaviour of the composite material will be concisely presented in the next sections.

The *dowel effect* appears when the reinforcement bar crosses a concrete–concrete interface and the bar is subjected to a slip displacement. If the concrete cover is thick enough, the slip causes a complex tri-axial state of stress.

The shear stress that can be transferred from one interface to another through the dowel effect depends on many parameters: the reinforcement ratio, diameter of the bar, the spacing between the bars, the concrete bar, strenght characteristics of concrete and the axial stresses inside the bars.

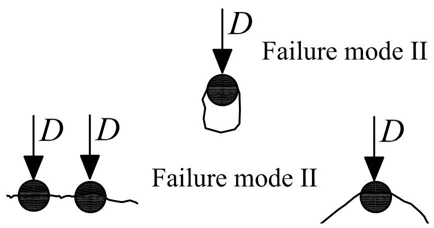

Fig. 1. – Failure modes for dowel action.

Accounting all these parameters two failure mechanisms have been observed (Fig 1): splitting failure of concrete cover at the lateral or bottom side of the member (failure mode I) and, second mechanism, crushing the concrete under the dowel and of the bar yelding (failure mode II). Another very important mechanism for shear transfer in reinforced concrete members which simultaneously is subjectd to shear and compression is called *aggregate interlock* (Fig 2). This mechanism is present both for smooth and, more realistic, the rough interfaces. We assume two interfaces of concrete split by a crack. The slip of the interfaces can occur under simultaneous increase of the crack with *w*. Due to the increase of the separation between the two faces of the crack, tensile stresses are introduced to the reinforcing bars corssing the interface. Then, the reinforcement introduces compression stresses in their vicinity. The phenomenon is known as the *clamping effect*. Using analytical relationship it is possible to find the resistance of the inteface to the imposed slip. In case of no reinforcement crossing the interface, the mechanism can be mobilized under a favourable effect of an external compressive load acting on the interface under the action of the prestressing forces. Even in zero stresses there is a potentiality of shear transfer through the interfaces.

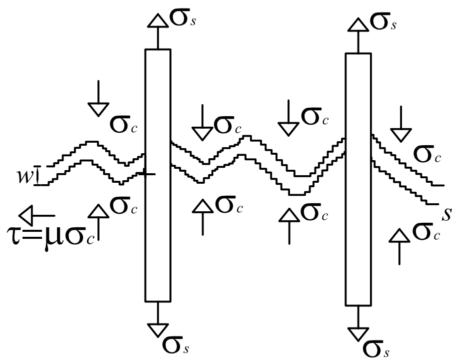

Fig. 2. – Aggregate interlock.

The *size effect* is strongly related to two separate notions: the way the crack grows and the energy release due to concrete cracking. First experimental and theoretical studies related to size effect in shear transfer were performed by Bazant (1984) and Carpinteri (1992). Based on linear elastic fracture mechanics, Bazant formulated a nominal strength concept (critical load related to a characteristic area). The concept is modelled in manner of tensile strength and geometry of the member. It has been proved that the crack grows on unit width and unit length in a linear manner with the energy consumption due to the process. This behaviour is characteristic for the linear-elastic interspace. Carpinteri, on the other hand, established the multifractility theory for fracture of the surfaces. Two concepts are introduced: negative geometries (stable cracking, loading cracking linear graphic, the decrease of loading produces the crack growth) and positive geometries (the behaviour curve has a cusp point; in the first stages, the crack grows proportional with the load, after that a decrease of the load makes the crack to propagate forward). The manifestation of size effects is related to the things related earlier. The behaviour of a reinforced concrete member depends on its geometry. It has been shown that for the stable cracking model at the levels of loading close to the postpeak level, fracture energy has a great contribution in defining the failure behaviour. The fracture energy helps the member in the transfer process of shear force after the tensile strength is reached. For punching test and experiments is compulsory to know all these issues and to know the finite element method modelling options. For punching, two of the most important ways of modelling the column and the flat slab are the strut-and-tie model and the rod model ("one-fourth" model - Uchida *et. al.* (1991)). Accounting all just these few aspects of plain or reinforced concrete it can be realized the complexity of the punching phenomenon. Counting the entire structural response of the flat–slab–column system, the need of ductility, a better behaviour on seismical areas and the addition of the gravitational masses, makes punching more complicated, though a resolvable problem. This is the reason why there is a lot of researches, nowadays, regarded to this matter. The scientists are searching for an effective formulation.

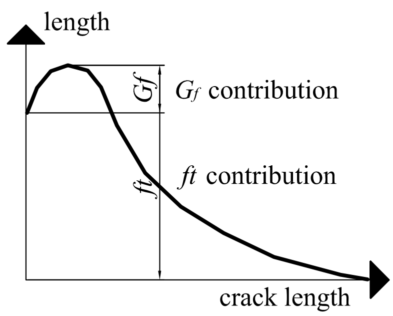

Fig. 3. – Loading-cracking curve, the influence of tensile strength and fracture energy at failure.

3. Punching Phenomenon

Punching occurs when a relatively small area is under the action of a concentrated force. The perimeter surrounding the loaded area is known as the control perimeter. Punching occurs when a conical plug of concrete suddenly perforates the slab above the column. As this failure mechanism is brittle (occurring without any warning sign and with a high reduction of the load carrying capacity) various constructive methods were developed to avoid it. Several mechanical theories were developed, verified or not, regarding flow of forces, crack growth during punching process and failure mechanism.

Two of the most important theories present opposite visions. Menétrey belief that the critical load is transferred by the tensile stresses through concrete towards the critical crack. On the other hand, Hallgren modifies Kinunen and Nylander classical theory, presented in CEB 168 (1985), advocating that the load is transferred by the concrete fibres in compression. CEB Bulletin 237 (1997) is dedicated to members without transverse reinforcement and to microscale behaviour of the commonly used heterogeneous material – concrete. Some of the most important related aspects from that bulletin are presented in the previous section. It is requisite to direct attention to this kind of members due to their brittle failure. Failure occurs before reinforcement bars yield; it is a local phenomenon as a result of the crack propagation.

4. Mechanical Models

The purpose of this chapter is to raid upon the classical punching models developed by Kinnunen-Nylander, Braestrup-Nielsen and Moe's.

a) *Flexural capacity approach*. Since in many punching tests the critical loads did not differ significantly from the flexural capacities in some early models punching strength of reinforced concrete slabs was derived from flexural capacity or combined with.

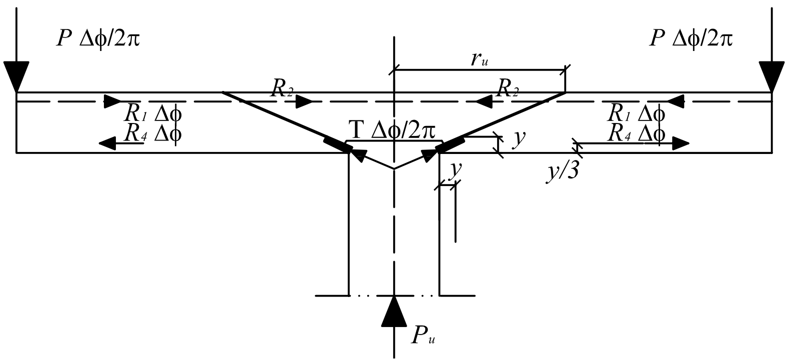

Fig. 4. – Kinnunen/Nylander model.

b) *Kinnunen-Nylander approach* (CEB 168 (1985)). The concept model consists in some rigid sectors outside the punching cone, carried by a triaxially compressed frustum cone starting from the edge of the cone and ending at the root of the crack (Fig 4). This was the first model that gained the best test results and is the most accurate model for the flow of forces within the tested element. More generally the approach may be characterized as a failure mechanism approach, where the rigid bodies separate at definite failure surfaces. In this case refers to the inclined shear crack surface. The location and geometry of the crack must be known before or calculated based on material properties and flat slab geometry. Kinnunen/Nylander mechanical modelling results are based on 61 circular flat slab elements connected on circular columns tested in 1960. The foundation of this model is mostly based on test observations and from non-linear finite element analyses: rigid sectors deflections, concrete and reinforced bars strain and crack growth process.

The ultimate punching strength for flat slabs without transverse reinforcement is calculated by two equations: first one that accounts the compressed concrete in section, in which the ultimate strength depends on the compressive strength of the concrete used σ_{cu}; the second relation is written for the yielding strength of reinforcement.

c) *Failure mechanism approaches* with concrete tensile stresses in the failure surface. A similar approach as presented before, with the consideration that another shear transfer is applied. The extensive and increasing research on fracture mechanics made Bazant (1987), Georgopoulos (1989), Menetrey (1994) to utilize the transfer of tensile stresses across the crack surface at the boundary of the punching cone.

d) *Plasticity approach* has been mainly used to determine the upper bound values for the punching load. A failure mechanism is defined in which the deformation is concentrated to a rotational symmetric area and the punching force is considered to be perpendicular on the flat slab. By equating the external work produced by the applied force with the internal work dissipated by the failure process an analytical formula is derived. The value of the upper bound, correlated with the test results, give the reducing factors for the compressive and tensile strength of the concrete. The flexural reinforcement bars are not taken into account in this formulation. Lower bound solutions were discussed by Braestrup in CEB Bulletin 168 (1985). Another simplified approach was developed by Marti & Thurliman (1977). Pralong (1982) studied lower bound solutions.

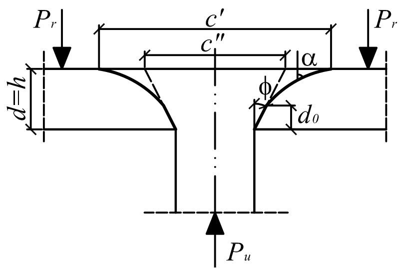

Fig. 5. – Braestrup/Nielsen *et al.* model.

e) *Braestrup/Nieslen et al. model* (Fig 5). This theoretical development was published first in 1976 based on plasticity. Counting that concrete is a perfect plastic material, the failure criterion by cracking is based on Coloumb's law ($\tau - - \sigma \tan\phi - c = 0$) and the tensile strength is set at a very low bound ($f_t = f_c/400$). The critical load, P_u, is calculated by comparing the fracture energy of the conical plug shell with the work performed by applied loads. The shape of the conical shell is added by a straight line and a caternary curve.

f) *Moe's model*, developed in 1963, is the base of the first American design codes for punching, ACI-318. The model was derived from tests on rectangular columns connected to rectangular flat-slabs. This model accounts both on different formulas the flexural strength (V_{flex}) and the shear carrying capacity (V_{shear}). This model is, in general, based on empirical formulae; does not take constitutive laws of the material or the geometry of the members.

g) *Strut-and-tie model*. It is considered a smeared model in which the shear transfer is made through concrete ties.

5. Code Equations

Every country has the right to govern its own design codes, depending on the economical influence, the financial and social resources. Combined with the deviating theories, the previous matters make that the design codes to be dissimilar. Comparison between design codes provoke the following two questions: "Which code gives the best approximation of the punching behaviour?" and "Which safety level is necessary for brittle punching?"

First differences occur by the reason of the magnitude of the safety coefficients, both in ultimate state and serviceability one. Most codes define a nominal punching force related to a control perimeter. Another difference comes from the manner that the compressive and tensile strength is determined (cube or cylinder).A comparison between the most popular and used two codes, Eurocode 2 and ACI-318, is made.

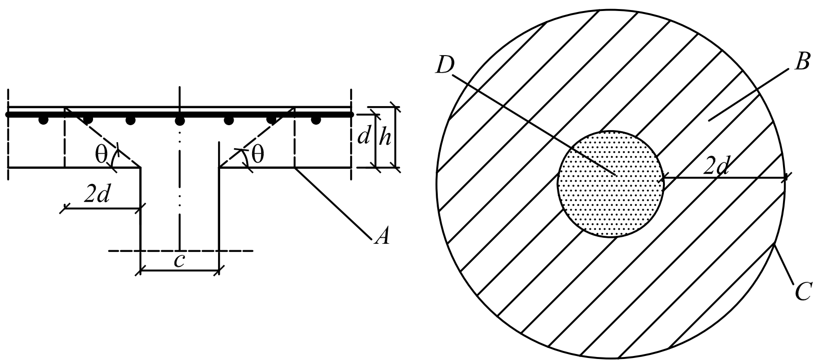

Fig. 6. – *A* – basic control section; *B* – basic control area, A_{cont}; *C* – basic control perimeter u_1; *D* – loaded area, A_{load}

Eurocode 2 is a design code whose relation is based on the phenomenon that occur in sections (ex. bending, compression, tension) not on straight relations, strictly related to reinforced or prestressed concrete members (column, beam, slab). There are some particularities that make the difference between the European and American code: the compressive strength of the concrete is determined on cylinder, there are specific formulas for high strength concrete (>C50/60), thee safety coefficient for material inhomogeneity is 1.50 for concrete and 1.15 for reinforcement, the concrete cover is related to durability, bond and fire resistance of the member and accounts the *in situ* imperfection, the control perimeter is 2d dimension measured from the face of the column. In EC2 the punching strength is defined to be a uni-axial shear strength and the punching capacity is calculated as concentrated force acting on a control perimeter.

Knowing that Model Code 90 is the "parent" of Eurocode, when comparing their prescriptions, it can be seen that the EC2 is a little bit more restrictive. Kordina (1994) tested both numerically and experimentally the punching phenomenon observed that the European design code approximates in a better manner the uniaxial punching strength and punching capacity. He proposed an updated formula by changing some coefficients and suggested an extension of the control perimeter. This was made due to the high stresses that occur in the transition zone (the exterior zone of the perimeter). By increasing the area the stresses can be neglected.

The European design code define the next relations: a) punching shear resistance of slabs and column bases without shear reinforcement,

$$v_{Rd,c} = C_{Rd,c}\eta_1 k(100\rho_l f_{ck})^{1/3} + k_1\sigma_{cp} \leq v_{\min} + k_1\sigma_{cp}, \tag{1}$$

where $\rho_l = \sqrt{\rho_{lx}\rho_{ly}} \leq 0.02$ relate to the bonded tension steel in y and z directions; $\eta = 1$ for normal concrete (in opposition to lightweight concrete); $C_{Rd,c},\ v_{\min},\ k_i$ – in national annex; b) punching shear resistance with shear reinforcement,

$$v_{Rd,cs} = 0.75 v_{R_{d,c}} + 1.5\frac{A_{sw} f_{ywd,\,\mathrm{ef}}}{s_r u_1}\sin\alpha, \quad k = 1 + \sqrt{\frac{200}{d}} \leq 2.0, \tag{2}$$

where: A_{sw} is the area of one perimeter of shear reinforcement around the column; s_r – the radial spacing of perimeters of shear reinforcement; $f_{ywd,\,\mathrm{ef}}$ – the effective design strength of the punching shear reinforcement; α – the angle betewwn the shear reinforcement and the plane of the slab; c) maximum punching shear resistance of cross section,

$$v_{Rd,\max} = 0.5 v f_{cd}. \tag{3}$$

The punching strength in ACI-318 depends on the strength of concrete, geometry of the column and the length of the control perimeter. The flexural reinforcement is not accounted in the punching capacity formula. The safety factors, both for reinforcement and concrete is 1.176. Punching capacity of a flat slab without shear reinforcement was provided by Digler and Ghali (1989)

$$v_c = \min\left[0.33\sqrt{f_c}0.83(2+\frac{4}{\beta_c})0.083\sqrt{f_c}(2+\frac{\alpha_0+d}{u_{\text{resp}}u_{\text{ext}}})\right], \quad (4)$$

where α_0 depends on the position of the columns in structure; β_c – the height of the column. Stirrups and stud-rails are both accepted as shear reinforcement for reinforced concrete flat slabs. If stirrup reinforcement is used, the punching capacity of reinforced flat slab is $V_c + V_s$, where

$$V_c = 0.167\sqrt{f_c}ud,\ \ V_{\max} = 0.5\sqrt{f_c}ud,\ \ V_s = A_{sw}f_y. \quad (5)$$

For stud-rail reinfocement, the magnitude of 0.5 coefficient, in the maximum punching capacity, is replaced with 0.67.

Eurocode 2, compared with the ACI-318 and aspects from the German and Brittish code, seems to be the most "coherent" code in designing the punching capacity and the ultimate shear strength. When choosing the reinforcement, stud-rails, in comparison with stirrups are better due to their flexibility; the in setting it up on site. Stirrups might be problematic when a stiff reinforcement framework is required.

6. Conclusions

New punching models have been developed in the last years due to the evolution of fracture mechanics and finite element modelling. The difference between classical theories and the new ones consists in the shear transfer mechanism and the influence of tensile strength. Still a final conclusion about the real influence and how much does it weight in final stages of behaviour is not stated yet. FEM has proved to be an excelent tool for predicting the failure mode, the deformations and the behaviour of the flat–slab–column connection. Similar results with the real experimental ones have been gained using this method. Several flat slab - column conections and their punching behaviour, in different configurations, have been tested during the last decades. Due to the progress of fracture mechanics tensile strength influence can be accounted in the nonlinear analysis. Since the elements' compressive and tensile strength have been calculated on different elements, differences occured. Even if there were used sizing factors, the differences on the strengths and geometries of the element, the responses were different from one element tested to another. It is compulsory that the next geometries and influencing factors must be similar for every element tested. This way the possible worries are avoided. Another important reasearch direction regarded punching would be high strength concrete and high performance concrete. There is no serious bank of tests regarded this issue established yet. The utilization of steel fibres in reinforced concrete could be another discussion topic.

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O INCURSIUNE ÎN STUDIUL STRĂPUNGERII PLANŞEELOR DALELOR DE BETON

(Rezumat)

La începutul anilor 60 s-au făcut numeroase studii legate de străpungerea planşeelor dalelor de beton. Evoluţia sistemelor de calcul şi a tehnologiei au influenţat şi această ramură a ingineriei. În acest moment există posibilitatea de a lua în calcul comportamentul neliniar al betonului armat şi precomprimat pentru a primi un răspuns structural cât mai fidel, comparativ cu realitatea. Fiind o problemă controversată, de-a lungul anilor s-au dezvoltat o mulţime de teorii mecanice de străpungere şi s-au realizat o mulţime de teste numerice şi de laborator. În acest moment, cercetătorii încearcă găsirea unei formule cât mai economice şi coerente pentru străpungere. Rolul acestei lucrări este de a face o incursiune în modelele teoretice clasice şi aspectele de comportare neliniară care trebuie luate în calcul pentru această situaţie.