

Fracture mechanics in the design of precast connections

Marco di Prisco, Francesco Iorio, Massimiliano Mauri & Marcello Scola

Department of Structural Engineering, Politecnico di Milano, Italy

ABSTRACT: In the last ten years, the anchor-bolt problem has become a significant reference problem for fracture mechanics applications and remains a harsh test for each computational model. Therefore detail design cannot be easily carried out without experimental tests. The paper shows three different precast connections. They require a correct design approach defining the most convenient failure mode, a suitable choice of safety coefficients to prevent other failure mechanisms, the reliability of the predictive equations suggested in the literature and a wide experimental investigation to confirm the design choices. The aim of the contribution is to check the reliability of the available empirical equations describing the collapses induced by fracture mechanics, to adopt the most simple analytical models able to estimate the bearing capacity of the other acting mechanisms and discuss a conceptual design approach able to define a univocal failure hierarchy for these details that are too often disregarded.

Keywords: fracture, anchor-bolt, precast connections, pull out, splitting, spalling

1 INTRODUCTION

Connections in precast structures are becoming objective of design. The fastening problem has been neglected by both steel and concrete building codes up to now, perhaps because it requires the knowledge of interface behavior and couples brittle concrete resistant mechanisms, based on fracture mechanics, to 3D constitutive behavior of concrete, strongly affected by boundary conditions, where loads are applied on very localized concrete portions.

According to Lynch and Burdette (1991), the advent of nuclear power plants and their attendant stringent documentation requirements greatly stimulated research in anchorage to concrete in the eighties. The previous knowledge on this subject is summarized by Klingner & Mendonca (1982a,b) in two papers. In the early nineties new experimental results were available on pullout and shear capacity of single or coupled anchors bolts and channel connections (Powell et al., 1991, 1992; Ueda et al. 1991).

The availability of new results (CEB 216, 1994) and the need to assign a general provision to the design of fastening in concrete, according to EC2

Ultimate and Limit State frame, led the CEB Task Group III/5 (under the guidance of Eligehausen) to the drawing up of the Bulletin 233 (1997). In this document the partial safety coefficients, that must be adopted for resistant mechanisms based on tensile strength and fracture mechanics of concrete are indicated. In the same document, serviceability limit states are also considered with reference to a maximum displacement at assigned load.

In the meantime, some displacement-controlled and carefully instrumented axial-symmetric or plane tests became a reference for advanced non-linear fracture mechanics and crack modeling. The anchor-bolt problem became a reference and was investigated in plane-stress state (Vervuurt, 1997; Cervenka & Saouma 1996; Slowik et al. 1995). It remains a very severe test for each computational model, because it is significantly affected by boundary conditions and its reproducibility is often undermined by contact phenomena between the bolt and the surrounding concrete. Moreover, the failure can involve the steel anchor, the concrete cone, the element edge, or can still induce bursting, pull-out or splitting as shown by Eligenhausen (CEB 216). For these reasons, computational analysis cannot be regarded as the only reference

for design, that requires reliable empirical equations and suitable experimental tests. The possible activation of different failure modes recommends that the designer chooses a preferred collapse mechanism that optimizes for instance ductility. This choice prevents the occurrence of other failure mechanisms causing a brittle failure, by means of suitable safe coefficients that take into account both the large scatter of peak loads (corresponding to brittle phenomena) and the uncertainties due to anchor installation (CEB 233).

The paper investigates three different precast connections that need a correct design approach: a simple bar channel, an anchor introduced in the corbel to guarantee the torsional capacity of a beam and a steel bracket bearing a façade panel.

The main objective of the contribution is to check the reliability of the empirical equations suggested in the literature for resistant mechanisms involving fracture mechanics, to compare them with the simplest analytical models able to describe steel collapse mechanisms based on limit analysis, and to discuss a conceptual design approach able to optimize these details that are too often disregarded.

2 FRACTURE MECHANICS MECHANISMS

According to literature (CEB 216, 233; Lieberum & Reinhardt 1989), the following empirical equations were taken into account to predict the bearing capacity expressed in terms of axial (N_{uk}) or shear (V_{uk}) characteristic loads of the resistant mechanisms associated to concrete fracture mechanics: cone (Eq. 1) and shear edge (Eq. 2) failure, pullout (Eq. 3), local splitting (Eq. 4; where A_1 indicates the loaded area and A_0 its homotetic external area).

$$N_{uk} = 12.6 f_{ck}^{0.5} h_{ef}^{1.5} \quad h_{ef} = \text{anchorage depth} \quad (1)$$

$$V_{uk} = 1.4 \phi^{0.5} f_{ck}^{0.5} c^{1.5} \cdot (1 + s/3c) \quad c = \text{cover} \quad (2)$$

$$N_{uk} = 0.3 f_{ck} \pi \phi h_{ef} \quad s = \text{bolt spacing} \quad (3)$$

$$N_{uk} = 0.7 f_{ck} \sqrt{\frac{A_0}{A_1}} \sqrt{\frac{40}{f_{ck}}} \quad (4)$$

3 EXAMPLES OF PRECAST CONNECTIONS

3.1 Test description and failure mechanisms

The first example is represented by a simple bar channel (Fig.1a) used to connect façade panels to

columns or to slabs or simply different structural elements to each other. It was investigated with reference to normal and shear force. In the former case a plastic hinge collapse due to the bending of the profile (Figs.1d,h), the extraction of the anchor bolt inducing a cone failure (Fig.1e), the crushing of the concrete surrounding the head of the anchor, the spalling of concrete (Fig.1i), the chipping of the steel profile (Figs.1h,i), the yielding and the failure of the anchor bolt (Fig.1f) are taken into account. Starting from these failure modes and after a choice of the main variables (thickness and geometry of the profile, length and diameter of the bolts, size of the bolt heads, bolts spacing, steel strength of both the bar channel and the bolt) an optimization analysis was performed.

The second example investigates the torsional connection of a precast beam to a corbel protruding from a precast column. The collapse can involve the bar pull-out (Fig.2b), the spalling of the surface aligned to the bar axis (Fig 2c), the failure of the steel bar (Fig.2d) or the concrete cone. The failure of the steel bar is expected to be the mechanism able to guarantee the most ductile and controlled behavior.

The last example refers to a steel bracket designed to bear the facade panel by the column. This connection can also reach different failure modes: the collapse of the steel bolt that allows the assembler to control the vertical position, the spalling of the concrete surrounding the steel box that lodges the steel threaded rod (Fig.3b), the extraction of the high bond bar pulled out to equilibrate the eccentricity of the vertical load and finally the yielding of bracket steel plates (Fig.3c). The last mechanism should be chosen by the designer, because its bearing capacity is the most repeatable and assures an adequate ductility.

3.2 Experimental set-up

The channel (Fig. 1a) was installed in a concrete prismatic specimen, made of plain concrete. In each preliminary test specimen four bar channels were installed. In two channels, one of the two bolts was free to move in vertical direction. The bolt heads were circular disks (3 mm thick), with a 25 mm diameter. The first type of test involved the extraction of the free bolt. In this case the contrast was offered by steel supports anchored at their ends by steel rods (Fig.1b).

A second type of test regarded the channel bending and it was carried out by using a screw located in the midspan and in a section close to the end (Figs.1h,d). The final tests on the optimized

profiles were carried out installing the bar-channels inside of longer specimens (Fig. 1c). Their shear bearing capacity was determined by using the test set-up described in Fig 1i. The force was applied by means of manual mechanical levers and

measured through a load cell. The displacement controlled tests were carried out, selecting a maximum vertical displacement rate variable in the range of 0.15-0.6 mm/min.

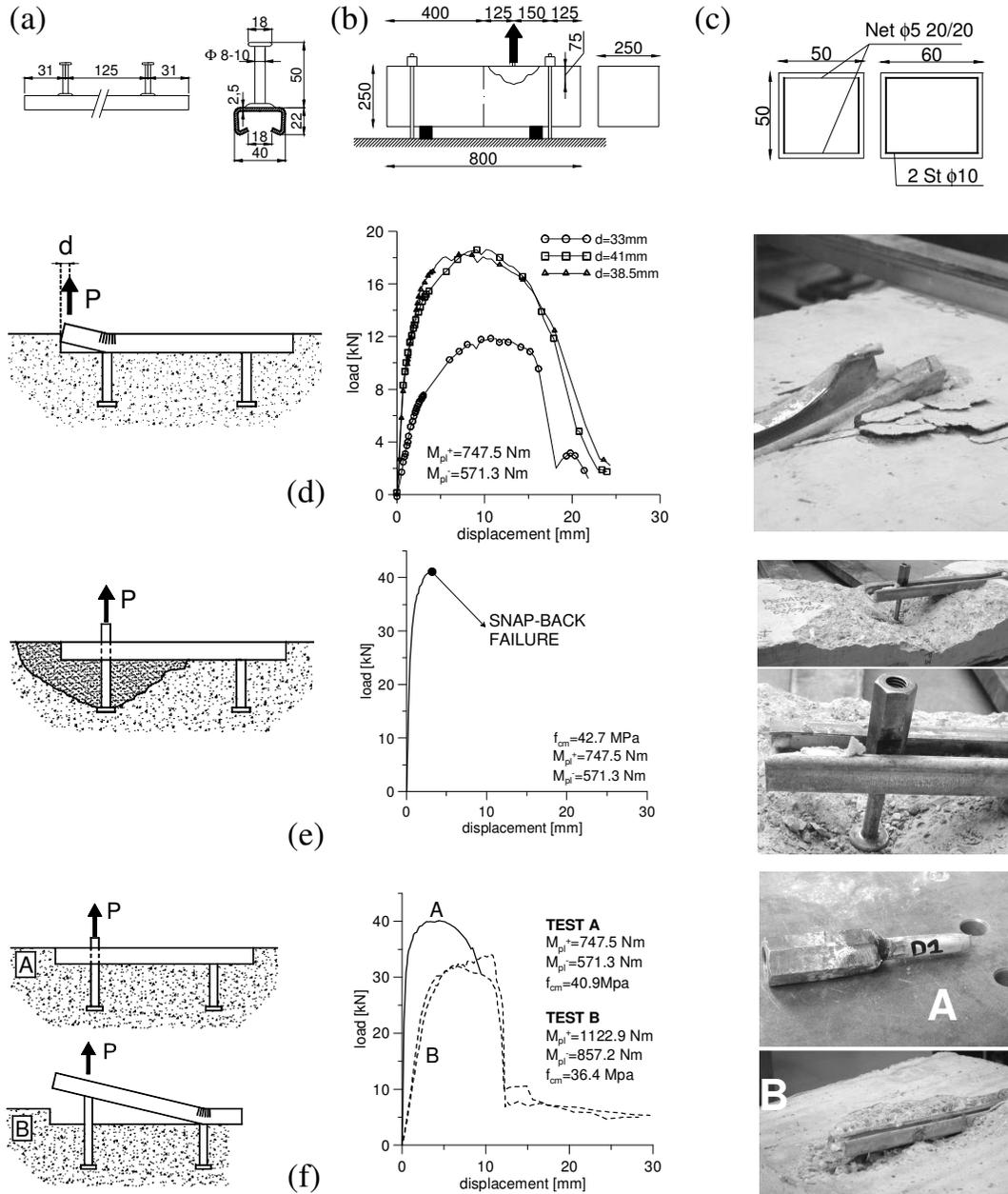


Figure 1. Bar channel: geometry of steel profile (a), and block specimen of preliminary tests (b), and final tests (c); cantilever failure (d), cone failure (e), bolt failure (f).

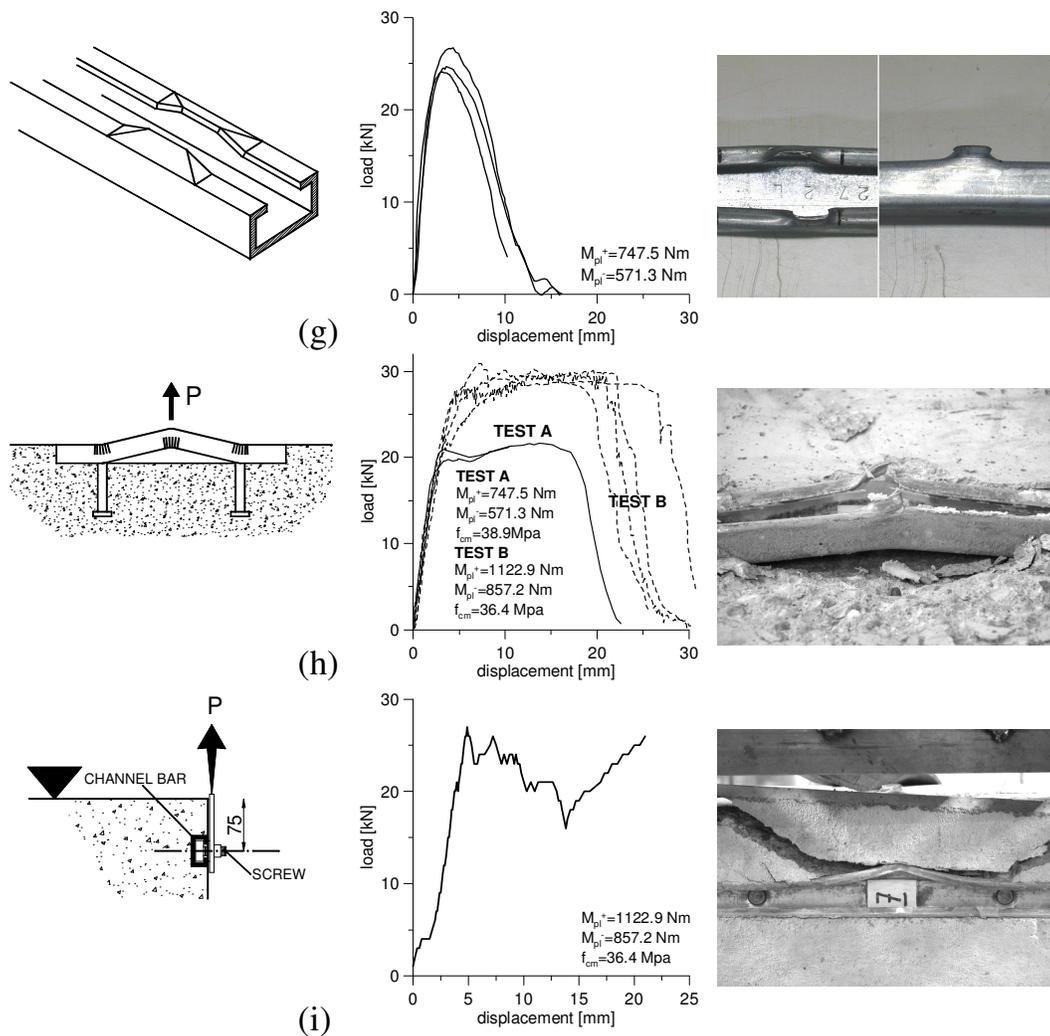


Figure 1. Bar channel: chipping failure (g), bending failure (h), shear failure (i).

In the second test series the specimens were reinforced concrete cubes (Fig. 2a). The load was applied through a hydraulic jack. Two plates connected the piston-end to the stretched bar ($\phi 24$ mm), screwed in the steel bush installed into the concrete specimen. The steel bush was welded to a steel bar. The high-bond steel bar diameter was always 20 mm. The geometry of the anchors is described in Figures 2b, c, d. To prevent rotation a steel cube embedded in a steel rigid frame connected with the main frame was used (Figure.2a).

A strut is placed symmetrically to the jack in

order to equilibrate the vertical force resultant and keeps the specimen loaded in pure torsion. The tests were displacement-controlled and the rates varied in the range 0.3-1 mm/min.

The last tests refer to a steel bracket designed to connect the facade panel to the column. The tests were carried out by using a Galdabini mechanical press with a bearing capacity of 5000 kN.

The mechanical set-up is shown in Figure 3a: the load was applied to the steel bracket by suitable levers. The tests were load-controlled and the applied load-speed was 1 kN/s up to specimen failure.

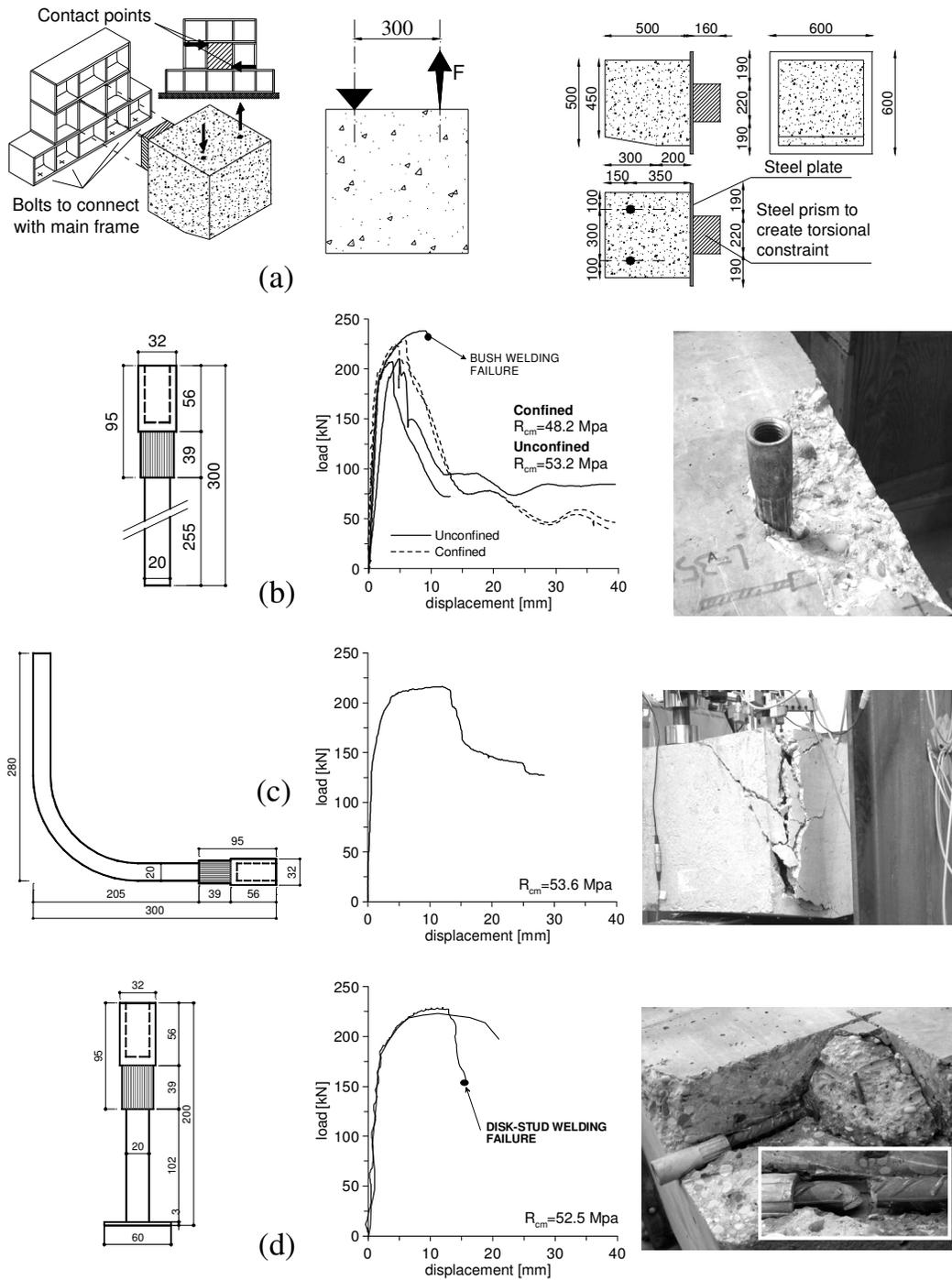


Figure 2. Corbel-beam connection: test set-up (a), pull out failure (b), splitting failure (c), steel bar failure (d).

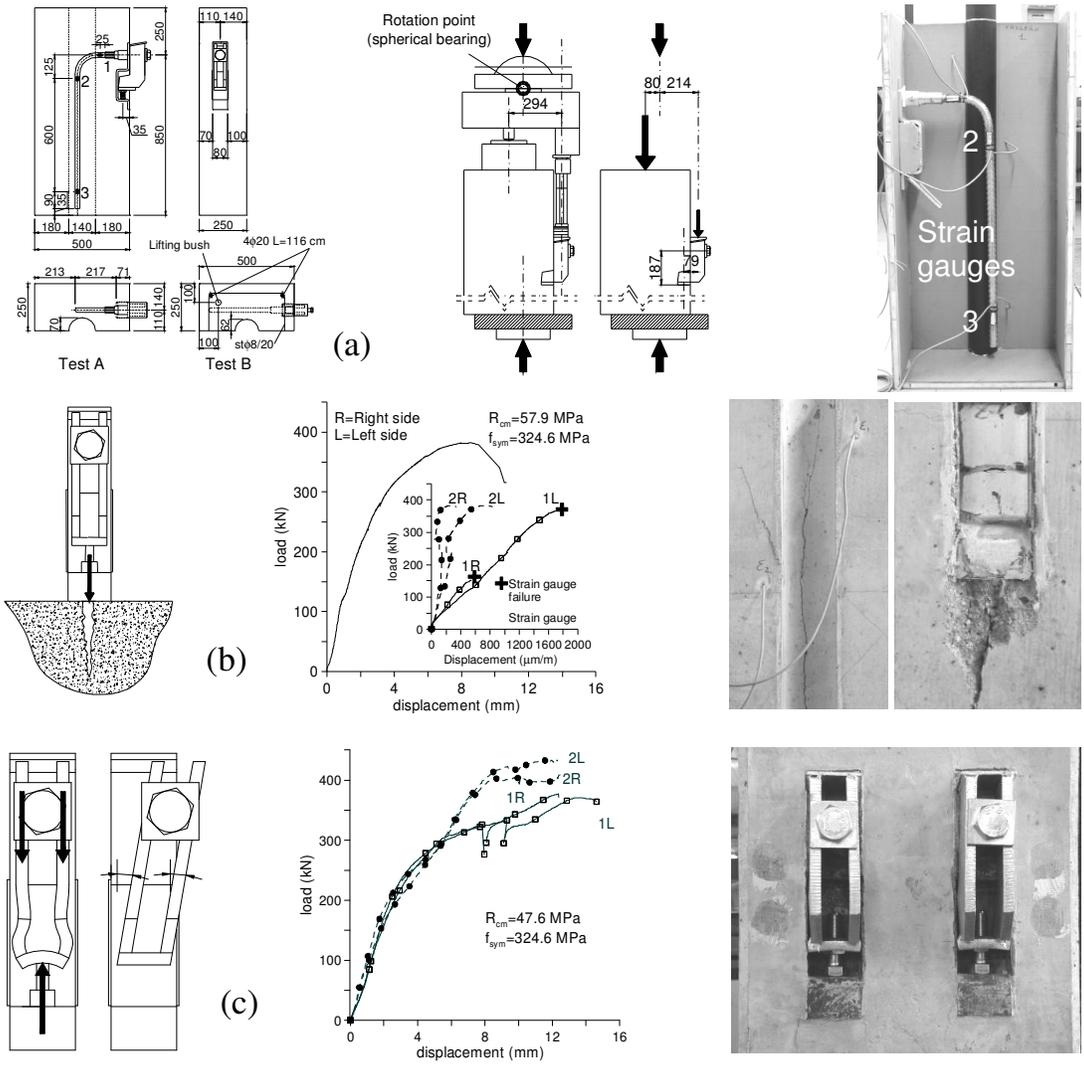


Figure 3. Steel bracket to beam facade panels test set-up (a), splitting failure (b), steel failure (c).

4 EXPERIMENTAL RESULTS

A commercial bar channel was first tested in order to check the bearing capacity of each resistant mechanism. The plastic hinge formed by a load acting out of the bolt interspace (Fig.1d) was significantly affected by the real lever arm fixed by the contact between the screw-head and the top wings of the cross-section profile. It must be taken into account the shape loss of the profile (chipping), because a simple limit analysis approach computed assuming an undeformed cross-section can estimate a failure load two times

larger than the measured one. The collapse is ductile, but the strong sensitivity of the real position of the load suggests the application of a large safety model coefficient ($\gamma_0=2$). By contrast, the prediction of a three plastic hinges mechanism for a central load (Fig.1h) is well fitted by limit analysis (error < 4% P_u), if the positive and negative bending moment are computed by testing, thus taking into account the local instability of the horizontal bottom plate. It is interesting to observe how the friction with concrete acting on the channel lateral surfaces affects only the initial stiffness of the mechanism, but does not increase

the maximum bearing capacity. The chipping failure obtained limiting the channel bending by means of two close supports (interspace = 70 mm; Fig.1g), is strongly affected by the free space between the screw-head and the inside width of the channel. A correct measure of this tolerance allows the designer to accurately predict the bearing capacity (error < 5%) by means of the kinematic approach based on yield-line limit analysis. A shear reduction of the tensile strength must be taken into account to reach the goal.

When the load is applied at a point close to the bolt, the best failure is represented by the yielding of the stem bolt (Fig.1f). The bolt geometry design (length, stem and head diameter, steel strength) must prevent the local crushing of the concrete pushed against the bolt-head and the concrete cone failure. The first failure load can be evaluated by multiplying the loaded surface for the compressive strength increased by a factor 11 with uncracked concrete ($P_{max}=145kN$). According to CEB 216, the concrete cone should be characterized by a 35° inclined surface. Therefore, the distance of the specimen border (125 mm) from the bolt axis is very close to the expected crack distance (about 107mm taking into account the effective anchorage depth of 75mm). The Equation 1 gives 45 kN for uncracked concrete, while the experimental value was equal to 42kN (error < 8%). The failure was not controlled in the softening regime due to the total compliance of the load chain concrete (Fig. 1e). It is interesting to observe that in this case cone and bolt-yielding failure loads are very close and hardening in the steel does not imply ductility, but favours a brittle failure. Finally also shear resistance (Fig.1i) was investigated. According to CEB 216 (Eq. 2), a load of 28.9kN can be determined if the characteristic compressive strength is estimated starting from the average value on cylinders directly extracted by the specimens. It is worth noting that the failure involves only concrete spalling and channel warping, but not dowel action (Gambarova & di Prisco, 1996) and for this reason a residual strength is shown after the peak.

The beam-corbels connections tested show three different mechanisms. Straight bars induced pull out failure, with the only exception of one test (Fig.2b), where the welded bush failed. The tests indicate a neglecting influence of the confinement introduced by steel reinforcement (square mesh $\phi 10/10$ each side) and a bond strength close to 10 MPa (Eq. 3) according to CEB 216 and FIB Bulletin (2000). By using a right bent-end, the pullout peak load does not change significantly, but

splitting appears in the post-peak behavior that keeping it more ductile. The best behavior is shown by the head stud, because the yielding of the bar is easy to predict either in terms of maximum load and ductility, by knowing the uniform stretching of the steel. The high failure load obtained in the last case is justified by a significant hardening ($f_t = 1.42 \cdot f_y$; $f_y = 500MPa$).

Finally the steel bracket designed to support façade panels highlights two different failure modes. The first is related to splitting of the unreinforced block specimen either along the vertical axis or locally under the compressed bolt (Fig.3b), the second one, related to reinforced specimen (Fig. 3c), involves steel bracket plates and induces a plastic bending of the bottom flange, or the warping of the vertical flanges with a partial rotation due to initial tolerances. The anchorage bars never reached the yielding failure ($f_{sy} = 500$ MPa). The local splitting in the reinforced specimen is prevented by the closest stirrup and the increase of bolt diameter from 20 to 24 mm and the related nut (from 30 to 36mm). In both the cases the real pressure values remain very high if the diffusion given by the steel-box thin plate is not taken into account and cannot be easily verified according to Lieberum & Reinhardt (1989) proposed equations (Eq. 4)

5 DISCUSSION

Experimental results of bar channel confirm a quite good prediction of bearing capacity offered by fracture resistant mechanisms like anchor bolt and spalling introduced by shear concentrated loads. By contrast the bending moment of open thin webbed steel profiles need a careful characterization in order to take into account the possible local instabilities of the profile. By using the experimental tests carried out on the commercial profile and limit analysis, an optimized channel bar can be designed (Figure 4), able to fail only according to the most ductile mechanisms (plastic hinges, chipping of bar channel and head-bolt yielding) and preventing the brittle mechanisms with suitable safety coefficients.

The torsional beam constraint introduced in the precast corbel exhibits the effectiveness of head studs, when the geometry is adjusted to prevent cone and bursting failure. In this problem steel hardening of the anchor activates pullout failure, which is not very easy to compute especially for long anchorage depths. The results confirm a bond strength of about $0.3f_c$, but it could depend on the

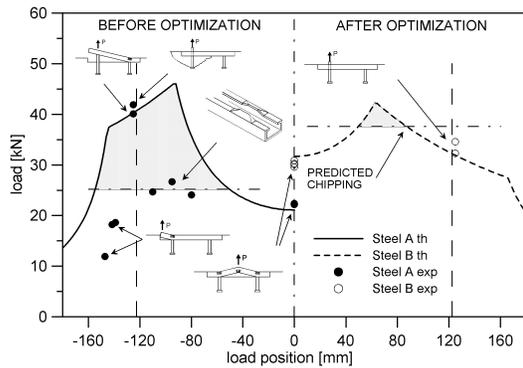


Figure 4: Bar channel: optimization results.

concrete strength, the depth/diameter ratio, the bush location inside the corbel, the active confinement exerted by the compressive force (equilibrating the pullout force in the torque transmitted between the beam and the corbel) and size-effect. The right-angle bent-end cannot prevent pullout, but increase significantly ductile behavior, even if this effect activates splitting and is much less predictable than the uniform yielding strength of head-studs.

The steel corbel supporting facade panels have remarked the need to test steel plates when their thickness changes even if the declared steel remains the same. In fact, the ductile collapse is controlled by steel plates plasticity and by the tolerances admitted in the mechanical device positioning. The local pressure exerted by the nut of the vertical threaded bolt needs a careful computation of the stress diffusion and must take into account the resources offered by the steel box and the possible confinement exerted by close stirrups. Simplified computations cannot satisfy the strength limits due to splitting, experimentally determined. In the investigated case a ratio close to 8 was computed between the maximum pressure estimated by means of a 45° diffusion and that computed by Finite Elements taking into account an elastic steel-box resting on an elastic Winkler soil, or an elastic concrete continuum. A simple rotating equilibrium allows the designer to compute the anchorage bar force that, in this case, remains always less than the predicted value.

6 CONCLUSIONS

The experimental investigation carried out on connections for precast structures show that design optimization of these details can guarantee a good prediction both in terms of load and ductility. The

reistant mechanisms based on fracture mechanics can be predicted mainly by empirical equations, while limit analysis can predict steel collapses. An upper limit of steel hardening strength could prevent the onset of other brittle mechanisms: in these cases ductility does not require steel hardening. Further research is needed about cyclic behavior of these mechanisms in order to extend the design to seismic actions, fire resistance, while a careful non-linear analysis could improve the knowledge on local pressure, influence of reinforcement, splitting and pullout.

ACKNOWLEDGEMENTS

The authors would like to thank Halfen and GL Locatelli S.p.A. for their financial and technical support. The authors are indebted to Prof. Roberto Felicetti for his precious contribution in the experimental activity.

REFERENCES

- CEB Bull. 216 1994. *Fastening to concrete and masonry structures*. London: Thomas Telford.
- CEB Bull. 233 1997. *Design of fastening in concrete*. London: Thomas Telford.
- Cervenka, J. & Saouma, V.E. 1996. Discrete crack analysis of anchor bolt pull-out. In F.H. Wittmann (ed.), *Fracture mechanics of concrete structures; Proc. intern. symp., Zurich, 25-28 July 1995*
- FIB Bull. 10 2000. Bond of reinforcement in concrete . State of the art report, T.G. Bond models chairman R. Tepfers.
- Gambarova, P.G. & di Prisco, M. 1996. Behavior and Analysis of R.C. Structures under Alternate Actions Inducing Inelastic Response: Interface Behavior", *CEB Bulletin 230*, Pubbl. T. Telford, London E14 4JD, 1996, capitolo 5, pp.98-133.
- Klingner, R.E. & Mendonca, J.A. 1982b. Shear capacity of short anchor bolts and welded studs: a literature review. *ACI J., Proceedings* 79(5): 339-349.
- Klingner, R.E. & Mendonca, J.A. 1982a. Tensile capacity of short anchor bolts and welded studs: a literature review. *ACI J., Proceedings* 79(4): 270-279.
- Lieberum and Reinhardt 1989. Strength of concrete on an extremely small bearing area. *ACI Struct. J.* 86(1): 67-76.
- Lynch, T.J. & Burdette, E.G. 1991. Some design considerations for anchors in concrete. *ACI Struct. J.* 88(1): 91-97.
- Powell, J.B., Burdette, E.G. & Oluokun, F.A. 1991. Prediction of pullout capacity of channel anchors. *ACI Struct. J.* 88(5): 624-630.
- Powell, J.B., Burdette, E.G. & Oluokun, F.A. 1992. Prediction of shear capacity of channel anchors in thin slabs. *ACI Struct. J.* 89(5): 624-630.
- Slowik, V., Alvaredo, A.M., Wittmann, F.H. 1995. Anchor pull-out tests – influence of boundary conditions and material properties. In F.H. Wittmann (ed.), *Fracture mechanics of concrete structures; Proc. intern. symp., Zurich, 25-28 July 1995*: 1529-1538. Freiburg: AEDIFICATIO Publishers.
- Ueda, T., Stitmannathum, B. & Matupayont, S. 1991. Experimental investigation on shear strength of bolt anchorage group. *ACI Struct. J.* 88(3): 624-630.: 1921-1930. Freiburg: AEDIFICATIO Publishers.
- Vervuurt, A., (1997), "Interface Fracture in concrete", Ph. D. Thesis, TU Delft.