Experimental and Numerical Study on the Anchorage of Safety Barriers to Bridge Corbels

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ABSTRACT: Post-installed systems for the anchorage of safety barriers to bridge corbels are widely used today thanks to their flexibility and easiness of installation. Because of commonly-found in-situ boundary constraints, however, the design requirements for fasteners and post-installed rebars are frequently not satisfied or only partially satisfied.
This paper presents an innovative solution concerning the placement of post-installed reinforcement in RC members.
With reference to the refurbishment of bridge corbels – which usually requires concrete removal in the damaged top layers – the proposed method is based on the introduction of additional U-shaped post-installed rebars connecting the existing portion of the corbel to the newly-cast top layer, in order to allow the transfer of the pull-out force exerted by the posts supporting the safety barrier. The layout investigated in this paper consists of three anchors connecting the end-plate of the post supporting the safety barrier to the corbel (a commonly-found layout in Italy). These anchors transfer the external actions (bending moment and shear) to the corbel thanks to the formation of a strut-and-tie system where the U-shaped rebars and the existing reinforcement play a crucial role. The tests on real-scale specimens are also modelled numerically and checked by means of design-oriented models.

1 INTRODUCTION

The refurbishment of existing infrastructures is becoming very important due to their ageing or lack of maintenance (Yeihea *et al.*, 2008). A common problem of existing bridges is the substitution or installation of safety barriers that must be replaced due to their ageing or increased demand. The substitution of safety barriers is usually associated with the partial reconstruction of the concrete corbel and the addition of post-installed reinforcing or anchoring bonded systems. Quite frequently, however, this affordable connection does not satisfy code requirements for the design of the connectors considered as overlapped rebars (according to CEN-EN1992-1) or as post-installed anchors (according to CEN-EN1992-4). The main challenges are the reduced thickness of the concrete corbel, which often does not guarantee a sufficient bonded length, and the limited edge distance preventing the development of the full concrete capacity when anchor theory is adopted (Eligehausen *et al*., 2006).
Nevertheless, the use of post-installed bonded anchors is very attractive due to their high flexibility and strength (Kunz *et al*., 2006). This study proposes a new solution that meets the common refurbishment practice requirements in Italy (with slight modifications) and is based on the removal and rebuilding of the damaged top concrete layer of the corbel. The novelty consists in the installation of additional U-shaped post-installed bonded rebars (with a prescribed spacing along the whole corbel length) before the new top concrete layer is cast. The safety barriers are then installed into the new reinforced corbel via three post-installed bonded bars (according to the typical layout adopted in Italy) that are positioned close to the post-installed bonded rebars.

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To evaluate the influence of the U-shaped rebars in the connection system, three full scale specimens were tested to check the effectiveness of the solution.
To study the transfer mechanism of the forces from the tensioned bars to the U-shaped rebars and their anchorage into the bridge deck, a 3D strut & tie model was developed and validated with numerical analysis. Finally, a strut-and-tie model of the whole corbel is presented to give the designers a user-friendly formulation to verify the whole concrete corbel.

2 EXPERIMENTAL INVESTIGATION

2.1 Sample preparation and test set-up

Three identical specimens composed of a reinforced concrete slab with dimensions 180 cm×100cm×20cm (Fig. 1a) and a corbel with dimensions 50cm×100cm×20cm were tested. The reinforcement in the corbel region was selected as a typical low reinforcement condition for Italian bridge corbels, while the reinforcement in the remaining portion of the slab was designed to avoid any possible premature failure during the test.
The samples were cast in two steps using C20/25 concrete and B450C rebars. The slab was cast first, and, after 28 days, three ∅12 U-shaped B450C rebars (Fig. 1b) were installed with an epoxy injection mortar with a characteristic bond strength of 14 MPa (ETA16/0143, uncracked concrete conditions). After 24 hours, the corbel was cast above the slab and, after an additional 28 days, three HZA (ETA 16/0143) threaded bars M20 were post-installed in the slab through the corbel.

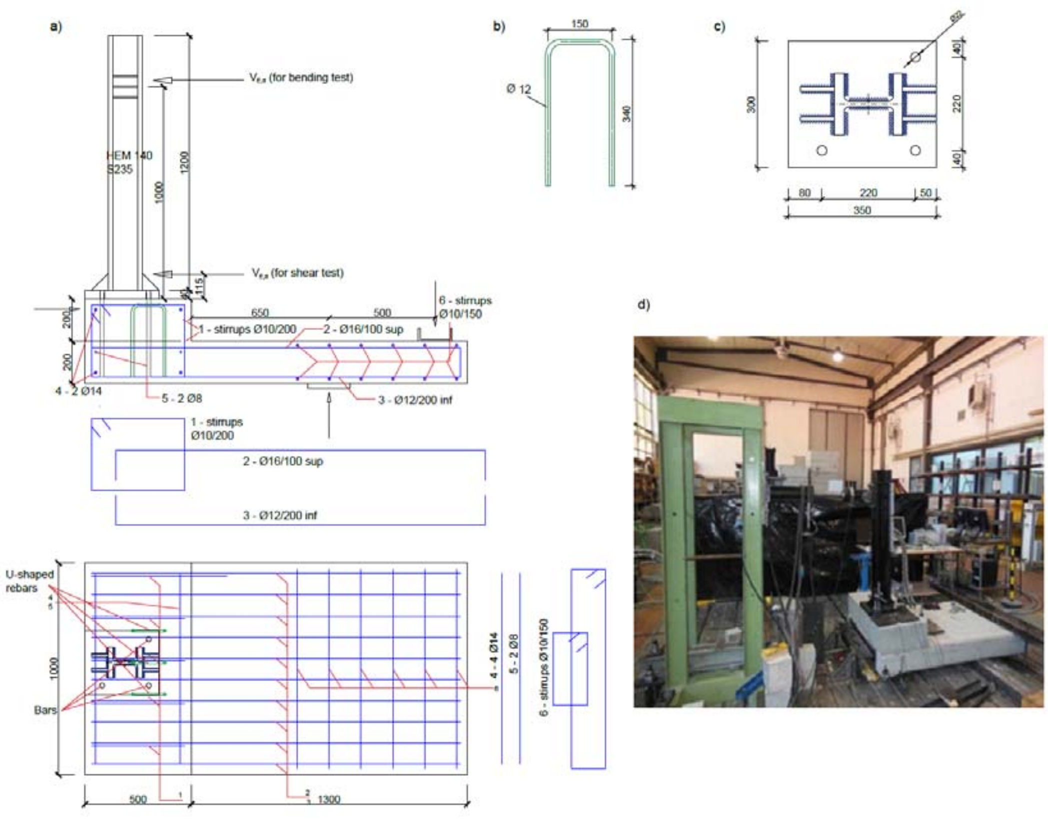

Figure 1. (a) Specimen and test set-up (b) U-shaped rebar (c) steel plate (d) test set-up (measures in mm).

The test configuration is shown in Fig. 1. The load was applied using a hydraulic jack located at a height of 100 cm from the steel plate. The specimen was supported in the middle of the slab and vertically restrained at a distance of 50 cm from the support. An additional horizontal restraint was placed in front of the specimen to avoid sliding.
The tests were displacement controlled at a constant rate of 0.05mm/s.
The load protocol consisted in (1) 3 loading cycles from 0 kN to 38 kN, (2) a subsequent increase in load up to 51 kN to check the crack pattern (load held for 2-3 minutes), (3) an increase in load up to 65 kN for test 1 and 2 and up to 84 kN for test 3, and (4) unloading
The load of 51 kN was chosen, as Ultimate Limit State Load, in accordance with common practice of design in Italy for safety barriers class H4 BP (edge bridge). It is noted that for exceptional actions the partial safety factor is 1 for both materials and actions. After each test, 3 cubes (side 150 mm) were tested according to EN 12390-3:2009 to evaluate the compressive strength of the concrete at the time of testing.
The displacements of the three post-installed anchors, the horizontal displacements at the bottom and at the top of the corbel and the sliding displacement of the specimen were measured via HBM LVDT transducers. The load was measured using a standard load cell (class I). All data were acquired with a HBM Spider 8 device with a sampling rate of 2Hz.

2.2 Experimental results

All specimens behaved in a similar way and no failure was observed. At a load level of about 47kN, two cracks (one for each lateral side) appeared at the corner between the slab and the corbel. In specimens 2 and 3, at a load of about 65-68 kN, some cracks were observed originating from bar A (see Fig. 3) and developing continuously up to the reached maximum load (about 84 kN). The main information regarding the crack patterns observed after the tests are summarized in Fig. 2.
The results in terms of load-displacement curves of specimen #3 are reported in Fig. 3 together with the results of the corresponding numerical analysis, which will be discussed in the following sections. The load vs. vertical displacement curves of the three post-installed anchors are plotted in Fig. 3a, and the horizontal displacements are plotted in Fig. 3b. After detecting a load reduction, the test was stopped at a load level of 84.07 kN.

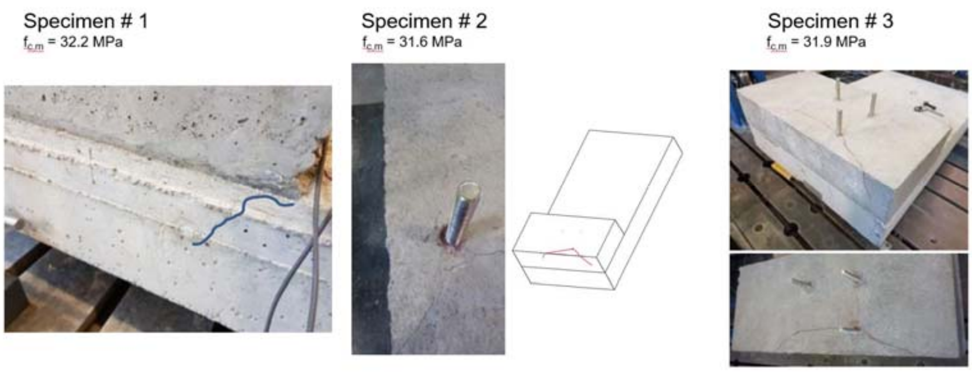

Figure 2. Crack patterns of tested specimens.

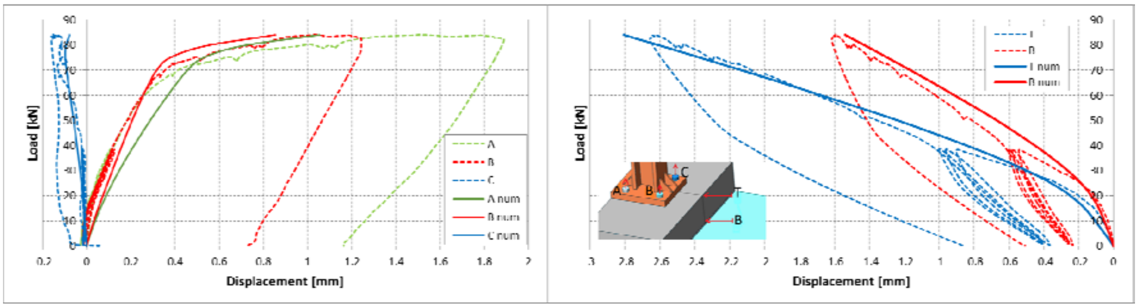

Figure 3. Specimen #3: Load – (a)anchors displacement curve (anchor C is in compression) and (b)horizontal displacements.

3 ANALYSIS OF THE ANCHORING SYSTEM

As shown in Fig. 4, the application of a horizontal force $V_{E,d}$ = 51 kN with a lever arm of 1 m, corresponding to the vertical distance between the connection and the point of application of the force, results in a combined bending moment ($M_{E,d}$ = 51 kNm) and shear load $V_{E,d}$ = 51 kN on the connection.
By applying equilibrium and compatibility equations, the tensile force T_B (= T_C=T/2) acting on a single anchor can be calculated (assuming a stiff plate).

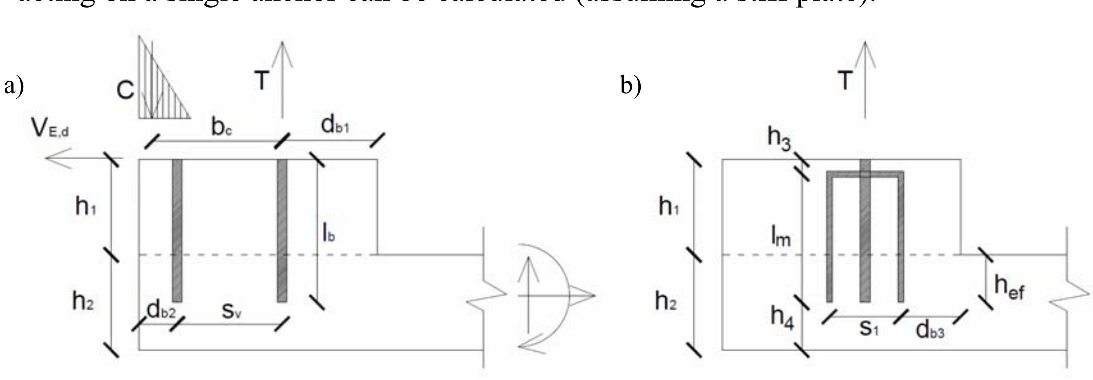

Figure 4. Geometry and applied loads on: (a) the corbel, (b) the additional U-shaped rebars.

A classical analysis based on anchor theory can easily show that, due to the geometrical constraints (limited edge distance/embedment depth) the two rear anchors (concrete cone and splitting due to tension) and the front anchors (edge failure due to shear) are not able to carry the applied tensile/shear loads (CEN-EN1992-4).
Nevertheless, the experiments showed that the connection with post-installed bonded U-shaped rebars behaved properly and the carrying capacity of the system was well beyond the predicted Ultimate Limit State (ULS). Therefore, to properly evaluate the capacity of the system, the U-shaped rebars must be accounted for.
The analysis of the geometry of the structural element suggests that the tensile load T is transferred from the two rear anchors to the U-shaped rebars that are anchored in the lower part of the bridge deck.
The experimental evidence, as well as the calculations based on anchor theory, showed that the weak point of the concrete corbel is the front anchor subjected to shear (only one anchor was considered. Thus, a practical suggestion is to use a slotted hole in the

steel base plate where the front anchor is positioned in order to transfer the shear force only to the rear anchors (B and C).

If this approach is adopted, the transfer mechanism of the load applied to the connection is expected to be as follows:

- the tensile load T applied to the two rear anchors will be transferred to the concrete corbel and the additional U-shaped rebars;
- the shear load $V_{E,d}$, applied to the two rear anchors bars only, will be transferred to the concrete corbel and to the transversal reinforcement (i.e. the existing stirrups);
- the compression load C generated by the steel plate will be spread into the concrete.

First, the transfer mechanism of the tensile load from the two rear bars (B and C) to the concrete corbel/U-shaped rebars must be investigated. Due to the actual geometry of the connection a 3D strut & tie model was chosen as the most appropriate approach.

As shown in Fig. 5, a force-transfer mechanism based on four compressed concrete struts connecting each post-installed anchor to the corners of the adjacent U-shaped rebars could be considered.

While the U-shaped rebars were placed symmetrically with respect to the two post-installed bars in the experiments, the model was developed to consider variations in geometry and tolerances representative of actual job-site conditions. This translated in the assumption that the three U-shaped rebars can be located in different positions (away from the post-installed anchors) while maintaining the same center-to-center spacing (S_2 = 150 mm, as for the tested configuration). This seems reasonable based on the fact that the installation of the U-shaped rebars is typically more easily controllable (and is happening before the corbel is cast). To broaden the applicability of the model to real job-site conditions, the transfer length L_{bd} is also assumed as a parameter(Kunz et. al, 2006).

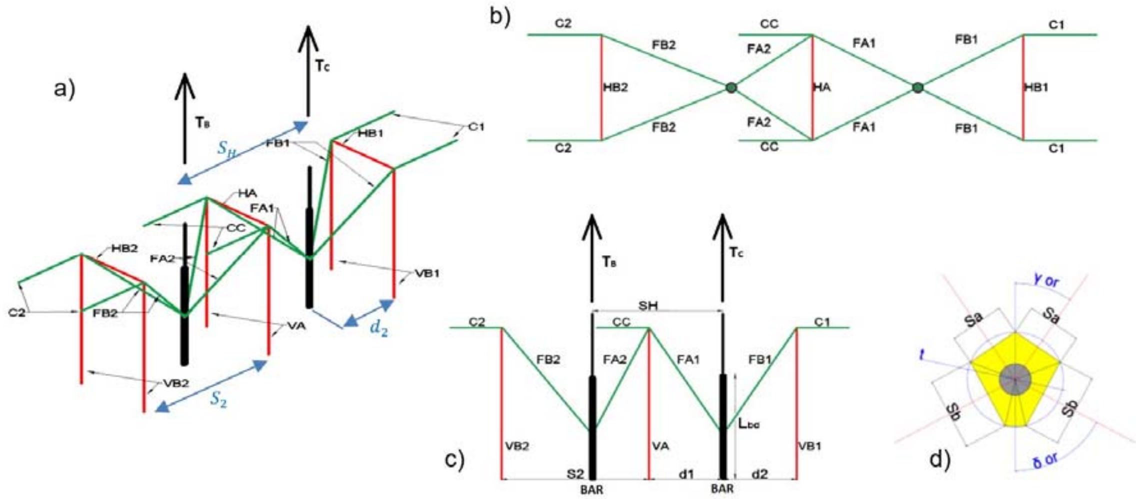

Figure 5. 3D strut & tie model (a) 3D view of the axis of the elements (b) plan and (c) vertical view of the U-shaped rebars (red), concrete strut (green) and post-installed bars (black) (d) nodal region around the bar.

Each group of concrete struts converging to each anchor is studied separately (inclination angles can be different when symmetry is not available) and equilibrium conditions need to be verified considering the horizontal components of the acting forces.

Evaluation of the stresses in the concrete struts is necessary to define their geometry and cross-sectional area. Furthermore, the three-dimensional geometry of the node between the post-installed anchors and the inclined concrete struts needs to be taken into account together with the dimensions of all the concrete struts, which depend on the radius of the circumscribed circle of the node's cross section t (Fig. 5d). Note that, given the minor importance of this parameter on the results of the model, its value can be conservatively fixed equal to 60 mm.

While all the expressions of forces and stresses could be determined (Cattaneo *et al.*, 2018), the most relevant expressions are the ones describing the vertical forces in the U-shaped rebars (V_{B1}, V_A and V_{B2} in Eq. 1), since the most critical aspect of the proposed solution is the verification of the U-shaped rebars and their anchorage into the concrete slab.

As shown in Fig. 5, the model allows the determination of the forces acting on the vertical legs of the U-shaped rebars as follows:

$$V_A = [T_B \cdot (2 \cdot S_2 - S_H)]/(2 \cdot S_2)\ ; \qquad V_{B1} = \frac{T_B \cdot (S_2 - d_2)}{2 \cdot S_2}\ ; \qquad V_{B2} = \frac{T_B \cdot (S_H - S_2 + d_2)}{2 \cdot S_2} \qquad (1)$$

For design purposes, all these actions must be lower than the maximum carrying capacity of the U-shaped rebars as follows:

$$V_i \leq A_S f_{yd} \qquad (2)$$

being A_s and f_{yd} the cross-section area of the U-shaped rebar and its yield strength, respectively.

Other failure modes, as related to the failure of the concrete struts or to the failure of the horizontal arms of the rebars, were shown to not control the design. Indeed, the horizontal forces in the U-shaped rebars are always lower than 20 kN (it is noted that the tensile steel capacity is equal to 50.84 kN) and the stresses in the concrete struts are always below 12 MPa. Thus, even when using a low strength concrete class (C20/25, as per the tested specimens), the concrete struts never fail.

In summary, for the geometry considered in this application, it seems that the system is able to transfer the applied tension loads from the bars to the U-shaped rebars. This conclusion is clearly applicable only if the U-shaped rebars are anchored properly in the lower portion of the corbel (bridge deck, that is). This latter condition can be easily verified in accordance with existing design codes (CEN-EN1992-4) or using commercial softwares (i.e. PROFIS Engineering). Finally, the model allowed an optimization of the system suggesting that the optimal solution to increase the allowable distance between U-shaped rebar and HZA) is to assume a spacing between U-shaped rebars of 200mm (instead of 150mm).

4 NUMERICAL ANALYSIS

To validate the strut-and-tie model and to assess the stress field in the corbel, a finite element non-linear model was developed using the software MIDAS FEA.

The concrete mechanical properties were chosen in accordance with CEN-EN1992-1 for a concrete class C20/25 (elastic modulus E_c=30GPa, average compressive strength f_{cm} =28MPa) and the steel was assumed to behave elastically (elastic modulus E_s=200GPa). The tensile behavior of the concrete was modelled using a linear total strain crack law characterized by a tensile strength f_{ct}=2.2MPa and a fracture energy $G_f = 73 \cdot f_{cm}^{0.18} = 132\ N/m$. Perfect bond between the steel and concrete interface was assumed.

The geometry of the corbel presents a cold joint between the upper face of the slab and the lower face of the corbel. This joint, which is a surface characterized by lower mechanical properties, was modelled using a thin layer of concrete elements (about 1 cm in size) with a reduced tensile strength (1.2MPa, Cattaneo and Giussani 2013, compared to the typical 2.2 MPa for a C20/25 concrete).

The comparison between the numerical analysis and the experimental results is shown in Figure 3, while the principal stresses field of the tested configuration are shown in Figure 6. It can be seen that stresses are transferred from the rebars to the U-shaped bars as schematically represented by the strut-and-tie model described in §4, and that the concrete corbel could be analyzed using an additional strut-and-tie model to help the designer design it.

To verify the applicability of the results, various analyzes were carried out considering different boundary conditions (experimental vs actual bridge), geometries (a short corbel with the height of 35 instead of 40 cm, a long corbel with the length of 70 cm instead of 50cm, double transverse reinforcement), and different tensile strengths of concrete. Figure 7 summarizes the main results. The selected test boundary conditions do not affect the results (Fig.7a vs 7b). The height/length of the corbel (Fig. 7c and d) seems to have limited influence on the results. On the other hand, the no-tension model highlights that the concrete tensile strength, f_{ct}, of the joint plays a primary role on the overall behavior of the corbel – the force transferred from the central U-shaped rebar to the lower portion of concrete slab increases as f_{ct} decreases from 1.2MPa to 0MPa (Fig.8).

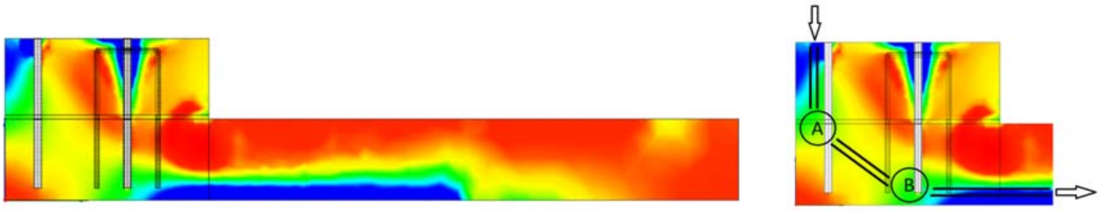

Figure 6. Distribution of principal stresses- tested configuration

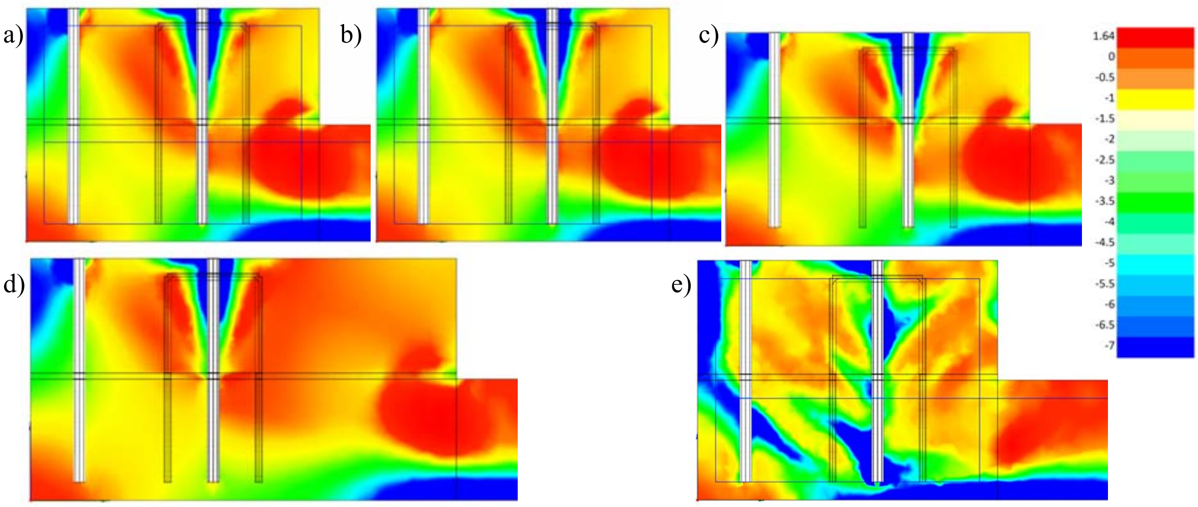

Figure 7. Stress field (a)tested (b) actual bridge (c) short (d)long (e) no-tension corbel (unit [MPa]).

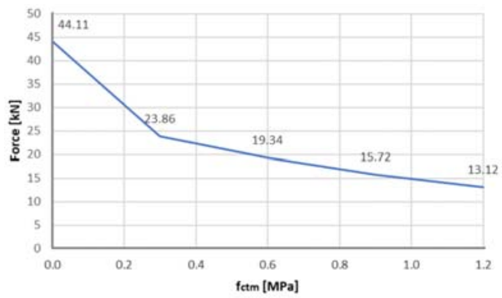

Figure 8. Force transferred by the U-shaped rebar as a function of the tensile strength

5 ANALYSIS OF THE CORBEL

Based on results of the numerical analysis, a 2D strut-and-tie model (Fig. 9) was developed to provide a series of user-friendly formulas for a quick verification of the concrete corbel.

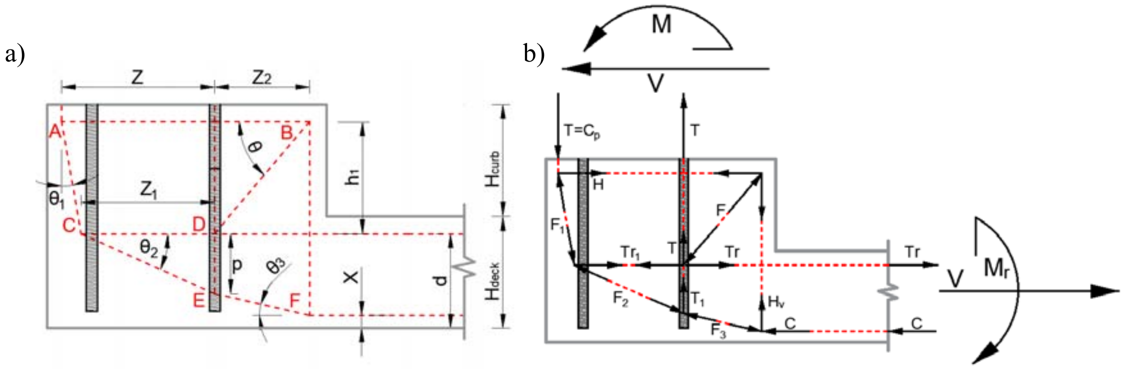

Figure 9 - Strut & tie model a) geometry and b) forces

The model (Fig.9) can be summarized as follows: the compressive force originating from the plate is first deviated toward the horizontal direction by the corbel's stirrups acting in tension. This force is then equilibrated by the tension in the vertical branch of the stirrups themselves and by another concrete strut converging to the node formed by the anchor and the upper (flexural) reinforcements of the deck (or slab).

The compressive strut originating from the external compression of the steel plate is further deviated by the presence of the upper reinforcement of the deck, the tensioned anchor and the vertical branch of the curb stirrups.

In summary, as shown in Fig. 9, equilibrium conditions must be fulfilled for six nodes (A-F).

The detailed analysis of the problem is presented in Cattaneo *et al.* (2018), together with the procedure to evaluate the main parameters of the strut-and-tie model and verify the corbel (See Table 1).

As a suggestion, the designer should verify that the minimum reinforcement present in the structure is sufficient to sustain the tensile stresses (Table 1, column "Design") and that the moment acting on the bridge cantilever, M_r, is lower than the design moment, M_{rd}.

$$M_r = M + V\left(H_{curb} + \frac{H_{deck}}{2} - c_s\right) \leq M_{rd} \quad (3)$$

The model is based on equilibrium principles, thus it is suitable for all practical applications. Nevertheless, some conditions (i.e. $z_1<0$ or $p<0$) lead to meaningless solutions. In addition, angles between struts and ties must be higher than 25°(ACI318, 2014).
It is noted that in the previous computations it was implicitly assumed that the system is able to transfer the applied shear force to the deck (or slab). A simple design verification is suggested to verify this assumption.
Furthermore, as mentioned above, it is advisable to provide a slotted hole in the steel plate to transfer the entire shear load to the rear anchors. In turn, the load transfer mechanism of the two rear anchors to the bottom of the slab can be verified following the cold-joint interface provisions of CEN/EN1992-1 or fib MC2010 – it is the authors' understanding that a verification in accordance with the latter provisions would be satisfied considering only the dowel action contribution of the anchors to the overall resistance across the interface.

Table 1 – Main quantities of the strut & tie model of the curb

Geometry	**Actions /Forces**	**Design**
Z, Z_2, h_1 ,H_{curb}, H_{deck} (see Fig. 9)	T, V, M	
$Z_1 = Z - h_1 \cdot \tan(\theta_1)$	$F_1 = \frac{T}{cos(\theta_1)}$	Area of stirrups within 2 steel plate width $A_T = \frac{\max(H_v,H)}{f_{yd}}$
c_s concrete cover	$H = F_1\, sen(\theta_1) + V_{Ed}$	Steel area at the top of the bridge deck $A'_s = \frac{T_r}{f_{yd}}$
S_1 =spacing between U-shaped rebars S_2 =spacing between the vertical branches of the U-shaped rebars	$F = \frac{H}{\cos(\theta)}$	Area of concrete under tension $Ac = 3S_1 \cdot 2S_2 \geq \frac{T_1}{f_{ctd}}$
X (see Fig. 9) - determined as the half of the neutral axis at the ultimate limit state of the slab with a width B=3S_1	$H_v = F\, sen(\theta)$	
$p = H_{curb} + H_{deck} - c_s - h_1 - X - Z_2 \cdot \tan(\theta_2)$	$C = \frac{M_{Ed} + V_{Ed} H_{curb}}{H_{deck} - c_s - x/2}$	
θ_1=10°	$T_r = C + V_{Ed}$	
$\theta = arctg\left(\frac{h_1}{Z_2}\right)$	$F_3 = \frac{C}{\cos(\theta_3)}$	
	$F_2 = \frac{F_1 \cos(\theta_1)}{sen(\theta_2)}$	
$\theta_2 = arctg\left(\frac{p}{Z_1}\right)$	$T_1 = F_2\, sen(\theta_2) - F_3\, sen(\theta_3)$	
$\theta_3 = arctg\left(\frac{H_v}{C}\right)$		

6 CONCLUSIONS

Based on the experimental, theoretical, and numerical analyses the following conclusions can be drawn:

- The system composed of only three anchors is not verified when anchor provisions are used.

- The proposed solution is effective and supported by experimental, theoretical, and numerical investigations.
- It is suggested to use a slotted hole for the front anchor to allow the rear anchors to carry the shear load.
- The interaction between the anchors and the U-shaped rebars can be studied by means of a local 3D strut-and-tie model, which highlights that the most stressed element are the legs of the U-shaped rebars
- From a more global point of view, a possible model for the interpretation of the overall behavior of the corbel was proposed. The designer could use that approach to check quickly if the reinforcement in the structure is enough to carry the external load.

Finally, the numerical analyses show that:

- the tested solution can be modeled accurately using the proposed simplified approaches.
- the stresses in the U-shaped rebars are significantly lower when evaluated considering the concrete tensile strength.
- the global behavior of the concrete is not affected by dense reinforcement and/or limited variation of the corbel geometry (height or length of the corbel).

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