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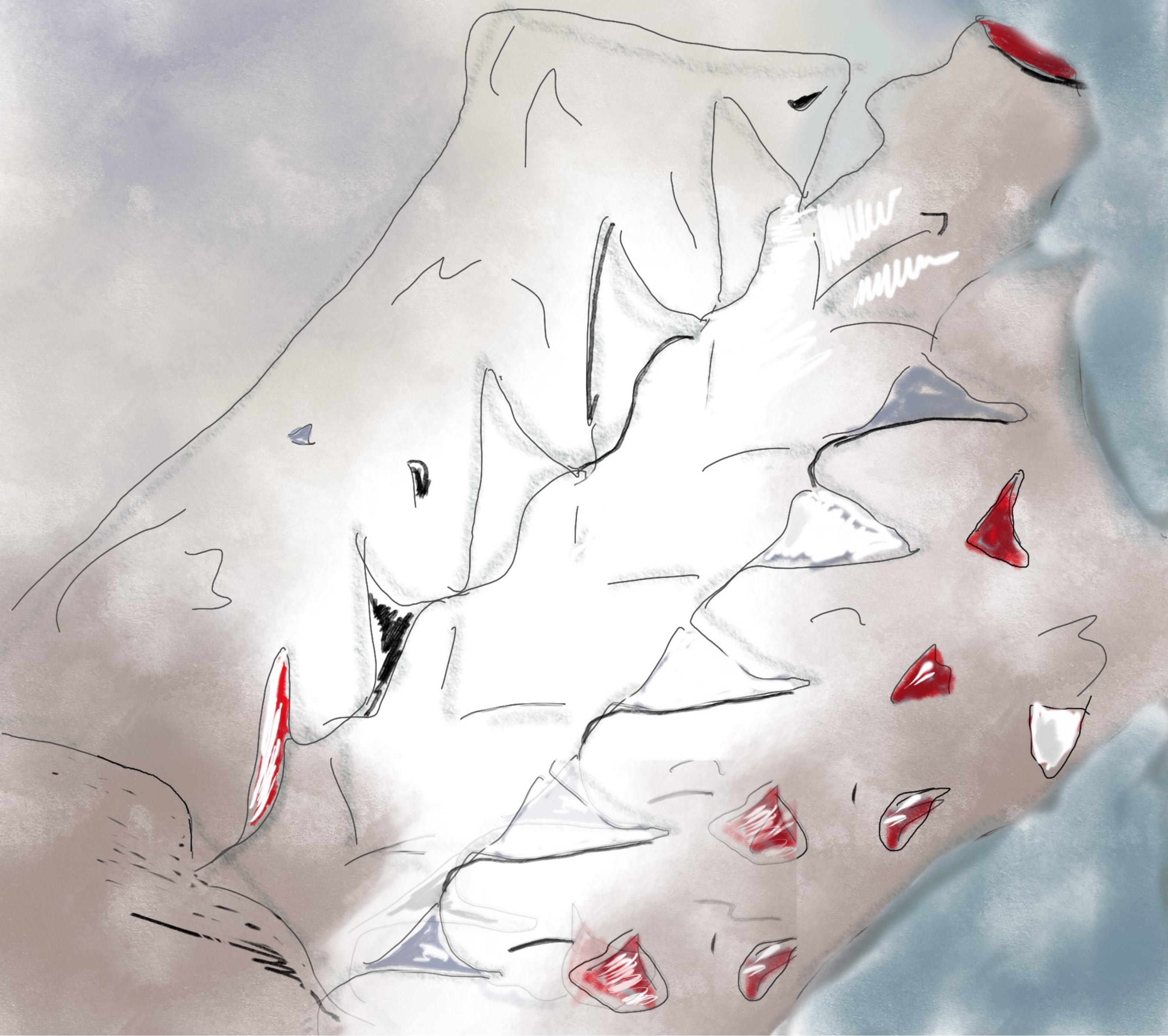

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Lap splice connection of new-to-existing rebars: a numerical study based on literature data

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ABSTRACT

Bond between steel reinforcement and concrete is the basic and fundamental mechanism which assures load transfer between the two materials in reinforced concrete elements. Even though bond has been widely investigated during the last decades, the number of parameters involved in the mechanism, as well as the number of possible geometrical configurations of the final element, are such that both models for the local bond-slip law and for anchorages or lap splices still need further investigation. As evidence of this, design-oriented documents, such as the *fib* Model Code, are constantly updated. Significant modifications of the bond models and the methods for the calculation of the anchorage length are foreseen in the next generation of codes.

The use of post-installed reinforcement offers a reliable solution for the connections in concrete structures, the strength and the stiffness being similar to traditional cast-in rebars. Many applications may be found in the rehabilitation and strengthening of existing structures. Nonetheless, post-installed rebars are becoming popular also in new constructions to make easier building and flexibility in design. Within this framework, structural designers often face the need of overlapping existing and new rebars, with a lack of design recommendations. This paper aims to investigate the load transfer of the new-to-existing lap splices. Numerical simulations were carried out with a commercial code, particularly an experiment from the literature was reviewed and numerically revaluated, also simulating the effects of different splice lengths, not counted in the original study. Inverse analysis was used to calibrate a local bond-slip law, which was the input for the following simulations. Failure mode and crack pattern are discussed showing that splitting is the dominant failure mode for short lap splices.

1 INTRODUCTION

1.1 Background

It is well known how bond is the fundamental mechanism for the functioning of reinforced concrete structures. State-of-art knowledge about bond of cast-in rebars was summarized in the *fib* bulletin n.10 [1], where the local bond behavior and models for the design of anchorages were extensively discussed. Nevertheless, a shared view about this topic is far to be achieved, such that significant changes are expected in the next generation of design guidelines. More recently, the introduction of efficient and reliable post-installed systems is driving a revolution in the construction industry.

Post-installed reinforcement with adhesive mortars is becoming the main design solution in many applications for repair and refurbishment of existing structures. Common cases are, for instance, the addition of new concrete elements like cantilevers or shear walls, or the substitution of damaged parts due to fire or earthquake. In addition, post-installed reinforcement can be effectively adopted to speed up the construction process of new structures. An example for column to foundation connections is presented in [2]. Hence, new contents are widened the public debate about bond in concrete. Main concerns about post-installed reinforcement are linked to possibility of reaching the same level of safety of the cast-in counterpart. For this reason, the current design approach is based on the hypothesis that post-installed reinforcement can be designed with the same rules for cast-in, as far as it exhibits a more favorable behavior. More details about guidelines are available in [3]. In the cited paper, a summary of the qualification procedure, as well as the design approach in Europe, was provided. Adhesive mortars for use in post-installed reinforcement shall be provided with a European Technical Approval (ETA) got based on a specific assessment procedure [4]. A system with this ETA can be used for lap splices and anchorages under static loading [5], under fire [6] and in seismic loading [7]. The anchorage length for post-installed rebars is evaluated using the same equation for cast-in rebars with a limitation regarding the bond strength; its value cannot be larger than the design bond strength calculated for cast-in rebars as function of the concrete class. A rather conservativism is claimed concerning the inherent limitations which arise in the use of such models also for post-installed reinforcement. Unfeasible anchorage lengths, for instance, results in case of rigid joints. Adhesive mortars are generally characterized by larger bond strengths when pullout governs the failure mechanism. Higher performances are due to a mechanism similar to mechanical interlock for cast-in ribbed bars, but which takes place along the roughness of the drilled hole with a more even distribution. However, higher stiffness of some adhesives may lead to a rather different transfer mechanism with a reduction of the transfer length. Consequently, bond stress concentration may be expected at the anchorage zone with excessive radial stresses and more risk of splitting [8].

1.2 Scope and research significance

In this paper, a discussion on the influence of lap splice length for connection of new-to-exiting rebars is presented. To this scope, a numerical investigation was carried out aiming to understand the load transfer mechanism in presence of post-installed reinforcement with high bond adhesives. The simulations account for different values of lap lengths, where the reference case is based on a previous experimental study from the literature, where post-installed reinforcement behavior was initially characterized by means of confined pullout tests (at the single rebar scale) and later evaluated in structural tests (at the sub-element scale) representing real site applications. An initial calibration is then carried out starting from such literature data, with a particular focus on adapting current local bond-slip law for cast-in rebars to the post-installed counterparts. Therefore, predictive analyses were developed varying the lap length. The results show how numerical simulations with Finite Elements Modelling (FEM) can be adopted by structural designers to predict the behavior of post-installed reinforcement. Insights about the load transfer and the crack pattern are given showing how higher bond strength and stiffness of post-installed reinforcement may lead to early failure by splitting.

The outline of the paper is as follows: a summary of the selected case study from the literature is presented as premise for the numerical investigation; then, a section titled “Numerical investigation” introduces both the calibration and the predictive modelling, which are listed in dedicated paragraphs. A brief discussion with comments on the failure modes and the crack patterns precedes the conclusions.

2 CASE STUDY FROM THE LITERATURE

The experiments carried out by Randl and Kunz [8]–[10] were taken as reference for the numerical investigation. The cited study dealt with the behavior of post-installed reinforcement highlighting possible issues in design and providing useful information for structural designers. It was early presented in the framework of the last Bond in Concrete conference of 2012 with a contribution regarding concrete splitting failure mode [8]. Then, an extended version of the proceeding was published on Structural Concrete, the journal of the *fib*, in which the experimental results were used to provide full guidance in design of post-installed reinforcement at ultimate and serviceability conditions [10]. A year later, a third contribution was presented at the *fib* Symposium 2015 thus concluding the research with evaluations about the long-term behavior of adhesives in presence of sustained loads [9]. The investigation hereby presented is mainly focused on the structural behavior of post-installed rebars, thus results from tests with sustained loads will not be considered.

In the experimental campaign, specific structural tests were performed, particularly (i) anchorage of a new corbel on an existing wall and (ii) a new cantilever added to a simply supported slab, also called "splice tests". The product dependency, which is well known in the field of post-installed fastenings, was taken into account by using two adhesives: (i) a hybrid mortar including organic and cementitious components; (ii) a high-bond epoxy mortar. In the original study, the different products were identified as "adhesive A" and "adhesive B", respectively. Their bond-slip behavior was evaluated with a series of confined pull-out tests. The tests were designed to favor splitting failure, namely a pair of closely spaced rebars was loaded in tension and the bond stress at failure was estimated from the measured peak loads. Such bond stresses were compared with predicted values according to a new approach based on Eurocode 2.

The following discussion is related to splice tests only; details of the corbel tests are available in the original publications. The slab specimens, both the simply supported part and the added cantilever, were cast with nominal C20/25 concrete. The cold joint interface (i.e. the joint between the two parts casted at different time) was roughened by high-pressure water jetting before cast the added concrete part. The diameter of reinforcement was 12 mm and the steel grade was BSt 550. Several specimens were built with different splice lengths ranging from 240 mm to 400 mm. It is worth noticing how the shortest splice corresponds to 20 times the nominal bar diameter, which is the upper limit for post-installed anchorages. As stated in [10], the embedment length was always significantly less than that calculated according to Eurocode 2. In all the splice tests, obviously the first crack was located at the interface of new-to-existing concrete, later other transversal cracks due to bending were observed mainly in the cantilever part. Post-installed reinforcement failure changed depending on the lap length. For specimens with short lap length, which were assembled with adhesive A only, failure was characterized by splitting cracks in the new concrete followed by pullout of the rebars. None of these specimens were provided with transversal reinforcement. The failure for larger lap lengths was influenced by (i) the adhesive type and by (ii) the presence of transverse reinforcement. Rebar yielding for adhesive A or bar pullout with splitting of the new concrete for adhesive B were observed in lack of any transversal reinforcement. The presence of closely spaced stirrups resulted in yielding of the reinforcing bars irrespective of the adopted adhesive. The splice tests were discussed and commented also with respect to deflections and crack widths providing further insights on serviceability. Interestingly, the stiffness of the mortar was found the main responsible for the differences in cantilever deflections and development of splitting cracks. The observations from the confined pullout tests, in fact, implied that the main load transfer is influenced by the higher bond stiffness of adhesives compared to cast-in-place rebars. As result, post-installed reinforcement creates larger splitting forces as observed in [11], where a rather similar behavior was observed from testing modified beam-end specimens. Finally, a method for the estimation of the crack widths was proposed by calculating the slip of the cast-in side of the bar according to *fib* Model Code 2010 and by adding the slip of the bonded part based on specific testing.

3 NUMERICAL INVESTIGATION

The behavior of lap splice connection of new-to-existing rebars is the topic of this numerical investigation. In absence of a specific experimental campaign, data from the literature were taken as reference in order (i) to calibrate the constitutive laws of the materials and (ii) to tune the modelling strategy. To this scope, confined pull-out tests and splice tests in [10] were first simulated; then, predictive modelling was developed to extend the mentioned experimental study. Numerical analyses, in fact, may provide a suitable and reliable strategy as an alternative way to laboratory or field testing [12].

The simulations with Finite Elements Method (FEM) were carried out with ATENA v5 from Červenka Consulting licensed to Politecnico di Milano. Some of the key features of the code are (i) the presence of advanced material models for concrete (e.g. smeared crack model, micro-plane model) and for reinforcement, (ii) a realistic visualization of the crack pattern. Further details about features, models and algorithms of the software are available in [13].

The matrix of the numerical models is presented in Table 1, where “PO” stands for pullout and “S” for splice test. It has to be remarked that each row of the table may identify a group of analyses, whenever a sensitivity study was performed.

Table 1: Matrix of the numerical models

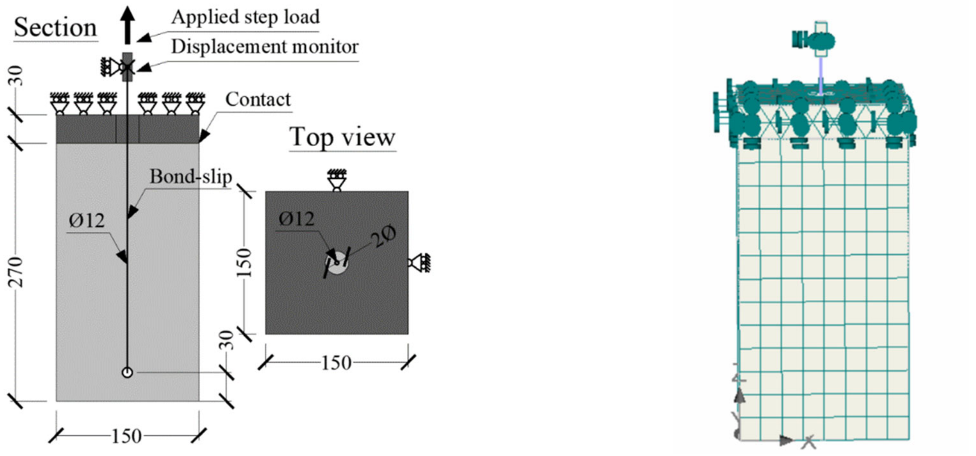
Code	∅ (mm)	l_b (mm)	lb / ∅ (-)
PO-240	12	240	20
S-240	12	240	20
S-360	12	360	30
S-400	12	400	33.3
S-480	12	480	40
S-600	12	600	50
S-720	12	720	60

Generally speaking, a numerical analysis is composed of many steps as (i) the input phase, (ii) the solution and (iii) the post-processing. A “good” simulation is usually sought through a proper combination of the input strategy and the algorithm for the solution. The adroit user can control some features of the solver to launch cost-efficient analyses while preserving the quality of the solution [14]. Numerical results are considered objective if they are not significantly affected by the adopted mesh [12]. To exclude the influence of the mesh size, a sensitivity analysis was performed for every simulated geometry. However, results are not shown due to the limited length of this contribution.

3.1 Calibration of the bond-slip law

In ATENA, rebars in reinforced concrete elements can be modelled as truss elements active in tension and compression depending on the presence of surrounding material. For instance, the response to compression of post-tensioned tendons can be disabled. When modelling reinforcing bars as embedded line elements, the code algorithm follows this procedure: (i) first the mesh of the solid element is created; (ii) then, the mesh of embedded linear isoparametric elements with two nodes (i.e. the reinforcing bars) is generated on the basis of the solid elements mesh. In this last stage, the degrees of freedom (DOFs) of the nodes belonging to the bar are kinematically linked to the DOFs of the underlying solid elements. The code allows for the definition of a bond-slip law along the embedded reinforcement [13]. In such case, many bond models are available, as the one from CEB-FIP model code 1990 or a user defined one.

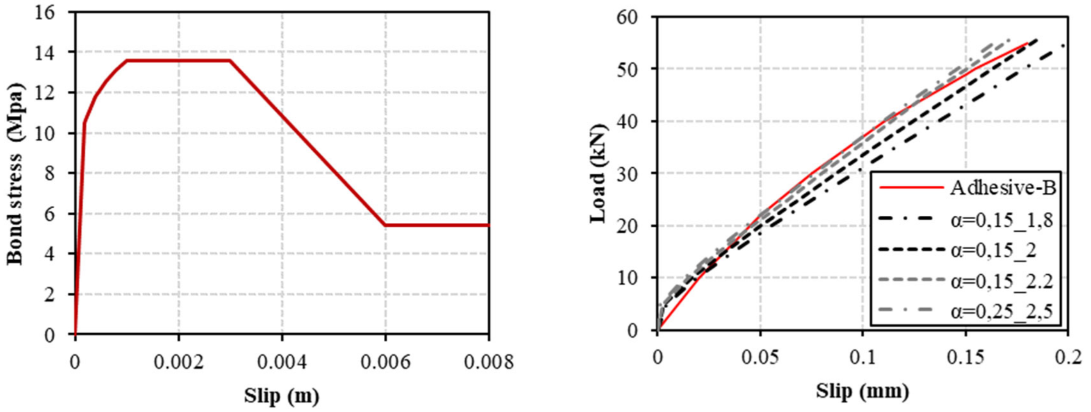
Confined pull-out tests on adhesive B in [10] were simulated in order to calibrate the bond-slip law for post-installed reinforcement. Behavior of high-bond epoxy mortar was found more interesting for the following parametric study on lap splices. A 3D domain was defined as follows (Figure 1): (i) a concrete block 150×150×270 mm^3; (ii) a steel plate 30 mm thick with a center hole equal to 2 times the bar diameter (i.e. 24 mm); (iii) a line element 12 mm diameter, embedded 240 mm in the concrete block and protruding 80 mm from the concrete surface; (iv) a small steel prism 10×10×30 mm^3 at the opposite end of the rebar with respect to the embedded part. Such prism was an artefact to avoid convergence issues due to a loaded end of a rebar outside concrete.



(a) (b)

Figure 1: Simulation of confined pullout: (a) model layout (measures in millimeters), (b) mesh and restraints.

An isotropic elastic material with 200 GPa Young's moduls was assigned to 3D steel elements. The model for the rebar was elastoplastic with isotropic and kinematic hardening. The yield and the tensile strengths were set from the corresponding values in [10]. With the only exception of compressive strength, which was equal to 46 MPa, concrete mechanical or fracture properties were not declared in the original study. Therefore, they were automatically generated by the software from the compressive strength by using *fib* Model Code 2010 equations with mean values format [15]. The constitutive model for concrete was smeared crack model with fixed crack [13]. The use of fixed crack was driven by the stress-strain field of the problem, which was not expected to experience significant modification in directions during the analysis. The mesh was structured for the concrete part with linear hexahedra and full integration scheme, while steel parts were meshed with linear tetrahedra. The average mesh size was approximately 20 mm. Full contact was assigned at steel-to-concrete interface thus also simulating the effect of friction on the confined surface. The analysis was load-controlled with a step rate of 1 kN/step. A full Newton scheme was adopted for the solution. The bond-slip law for the embedded rebar was derived starting from the model for cast-in reinforcement and assuming “unconfined concrete” and “good bond conditions”. Assuming the model from CEB-FIP Model Code 1990, different trials for the α exponent and for τ_{max} were repeated in order to fit the experimental curve (Figure 2b). In absence of more detailed information, same slip values of cast-in reinforcement were assumed. The best-fit (Figure 2a) was obtained for α and τ_{max} equal to 0.15 and 2.0, respectively.



(a) (b)

Figure 2: Simulation of confined pullout: (a) back-calculated local bond-slip law, (b) numerical Vs experimental curves.

3.2 Simulation of the slab tests

Splice test with 400 mm lap length and without transversal reinforcement in [10] was simulated to validate the calibrated bond-slip law for post-installed reinforcement. The layout of the model, in which the position of reinforcing bars is highlighted, is shown in Figure 3. The modelling strategy was similar to the previous case, with concrete modelled as 3D volumes and the rebars as line elements. Thick steel plates in contact with concrete were used to simulate the position of the supports and to apply the load. The model was restrained in correspondence to the steel plates of the supports. Full contact was assigned to all steel-to-concrete contacts. The analysis was displacement-controlled with a step-increasing displacement imposed at the steel plate on the tip of the cantilever. The constitutive models for the materials were the same as the pullout test simulation, with difference in values of concrete parameters which were generated from a concrete strength of 41 MPa. The bond-slip law for rebars was different depending on the position in the domain. For all cast-in rebars, the shape of the bond-slip curve was automatically generated from the assumed concrete strength. Conversely, the previously calibrated bond-slip law was assigned to the post-installed part of lap splices. Hook ends of rebars were modelled as “no-slip” nodes. The interface of new-to-existing concrete was modelled by using an interface material with Mohr-Coulomb behavior (i.e. friction behavior). Such a model is available in ATENA and consists of a classic “penalty approach” with cohesion (i.e. tensile strength of the interface) and residual friction properties (i.e. aggregate interlock). The introduction of an interface leads to additional non-linearities; therefore, the solution was searched through the arc-length method. The model was meshed with linear hexahedra for concrete and linear tetrahedra for steel parts. The mesh was rather coarse to speed up the analyses, nevertheless the average mesh size was at least 65 mm to avoid shear locking issue.

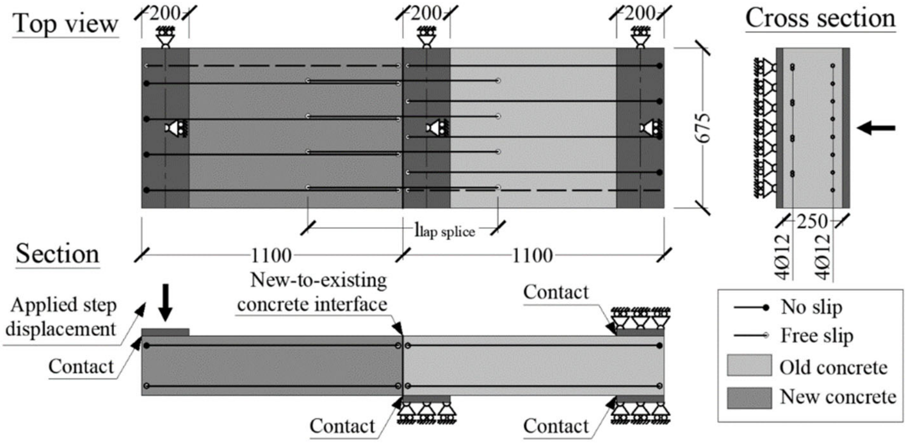
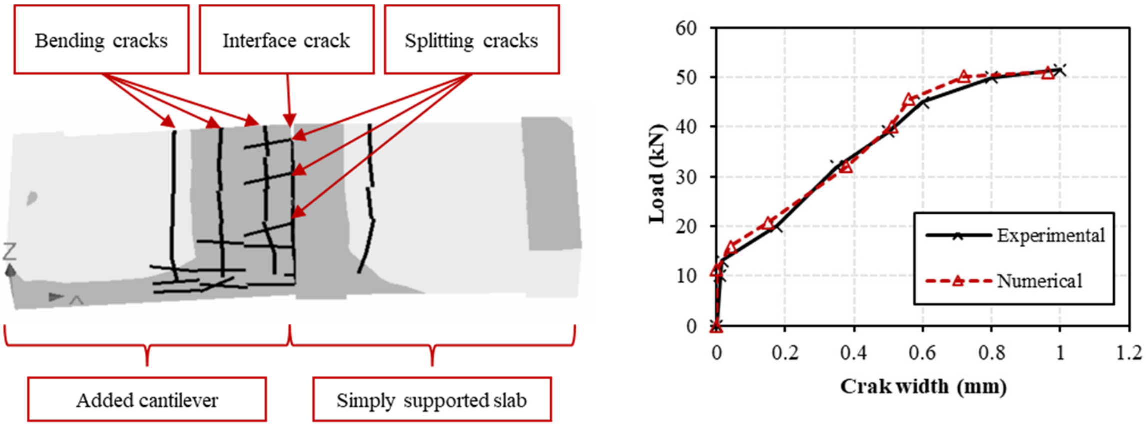


Figure 3: Simulation of splice tests: model layout (measures in millimeters).

A preliminary parametric study upon some of the most important parameters for concrete fracture was carried out. In fact, in absence of detailed knowledge, sensitivity to change in concrete parameters should be assessed. Therefore, the analyses were repeated many times as the tensile strength and the fracture energy in the range of 1.25÷2.5MPa and 77÷144 Nm, respectively. The ranges are representative of typical low strength mixes. However, it has to be pointed out that fracture energy strongly depends on the aggregate size and type and results could be affected by some uncertainties. The best fit combination was found for a tensile strength value in the range 1.75 MPa to 2.0 MPa and for a facture energy value equal to 77 Nm. The crack pattern at the peak load was characterized by the presence of bending cracks in the added cantilever and splitting cracks in correspondence of the cast-in side of the lap splices (Figure 4a). The numerical load-crack width curve is in good agreement with the experimental one (Figure 4b). It must be remarked that crack width values were taken as the horizontal displacement of the edge of the cantilever with respect to the simply supported part.

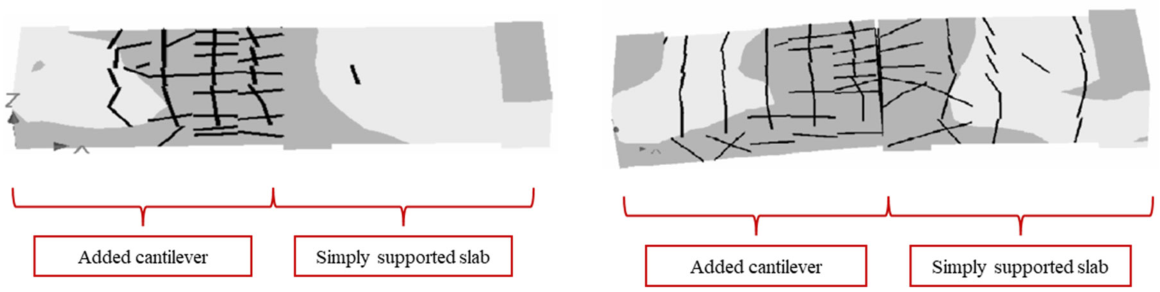


(a) (b)

Figure 4: S-400 simulation: (a) crack pattern, (b) numerical Vs experimental curves for f_{ct} = 2.0 MPa and G_f = 77 Nm.

3.3 Parametric study on lap splice length

The possibility to vary the length of new-to-existing rebars was numerically investigated via parametric analyses. The simulations were repeated by using the previously validated model but with different rebar lap splice lengths in the range 240÷720 mm. Considering two different values for the concrete tensile strength, the total number of analyses was equal to 10 with 5 different lap splice lengths. Significant differences in the failure modes, and hence in the peak loads, can be observed from the numerical results. Splitting cracks in the new concrete part with a rather brittle behavior characterized the model with shorter lap length (Figure 5a), also in presence of a large concrete cover as 3 bar diameters (i.e. 46 mm). On the other hand, yielding of reinforcing bars with development of multiple bending cracks were typical of longer splice lengths (Figure 5b).



(a) (b)

Figure 5: Crack pattern from the parametric study: (a) S-240, (b) S-720.

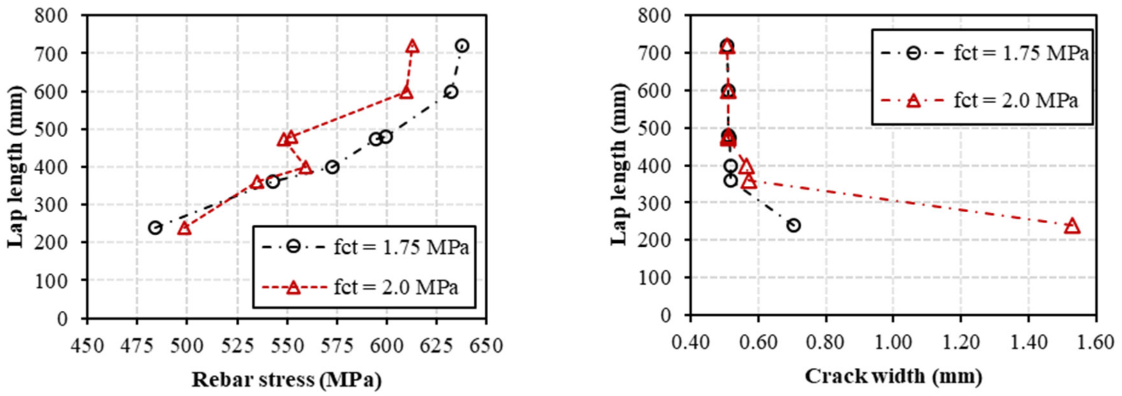
4 DISCUSSION

In this section, results from the parametric study on lap splice length are discussed focusing on (i) crack pattern, (ii), rebars stresses and (iii) crack width.

The numerical results, particularly the crack patterns, were consistent with the experimental observations in [10], despite differences in the investigated lengths. Higher bond strength and higher stiffness of some adhesive mortars, in fact, seem

related to a different load transfer which takes place at a lower distance, thus creating larger splitting forces [10]. As consequence, in lack of any confinement, splitting cracks prevent reinforcement from yielding.

Plots of Figure 6 shows average rebar stresses and average crack widths as function of the lap splice length. The values were evaluated from the binary files of the analyses by defining specific monitors in the domain: (i) rebars section at the cold-joint interface for stresses; (ii) top edge cantilever for crack widths indirectly measured as nodal displacement. Results are plotted for the two different values of concrete tensile strength used in the simulations. Yielding of the rebar was achieved only after 600 mm. It is worth noting the snap-back in the results for f_{ct} = 2.0 MPa at 480 mm lap length. In this case, the reduction of rebar stresses, with respect the 400 mm case, may be due to a change in the crack direction. The increase in the lap splice length seems associated to a reduction of the crack width at the interface of the two parts casted at different times. The 240 mm case was characterized by wider crack width which could be related to premature bond failure of rebars with significant slip.



(a) (b)

Figure 6: Parametric study: (a) lap length-rebar stress, (b) lap length-crack width.

5 CONCLUSIONS

In reinforced concrete structures, anchorage of reinforcing bars is designed as function of the longitudinal forces to be transferred into concrete. The total transfer is generally preferred promoting steel failure over brittle concrete-related failure modes, namely concrete splitting, or pullout of the bar. Many detailing for anchorage can be found in real applications like end anchorages or lap splices. The latter usually occurs when the length of a rebar is insufficient; in such condition, the longitudinal forces are transferred from that bar to another through the surrounding concrete. Lap splices are also very common for site applications with post-installed reinforcement. Post-installed systems with adhesive mortars are very common on modern construction sites. In fact, they represent a reliable and robust alternative to traditional cast-in rebars, particularly for repair and refurbishment. Thus, lap splice connections with post-installed reinforcement can be found whenever a new concrete part is added to an existing structure. Current guidelines allow the design of post-installed reinforcement the same way of cast-in connections with limitations on the bond strength. However, in order to get a safe design, other aspects should be taken into account more than the mere resistance.

Within this framework, the behavior of lap splice connections of new-to-existing rebars was numerically investigated. A commercial code with a built-in local bond-slip model was used for the simulations. The calibration of the bond-slip law, as well as that of the modelling strategy, was carried out through inverse analysis from literature data. Confined pullout and specific structural tests with lap splices in a new added cantilever were taken as reference. The results were correctly reproduced both in terms of failure mode and crack pattern, with minor inconsistencies probably related to insufficient details about material properties. Successively, a parametric study was developed varying the lapped length in the simulation of the same structural test. The results confirmed that short lap splice lengths with high-bond adhesive mortars may lead to a stress concentration with potential early failure due to concrete splitting. Such an effect can be mitigated by adopting longer lap splices to get yielding of reinforcement. However, in lack of any transversal reinforcement, splitting cracks may affect the new concrete portion irrespective of the lapped length, as observed from the crack contour plots.

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