USE OF POST-INSTALLED REINFORCEMENT FOR INTERFACE SHEAR IN THE RETROFIT OF CONCRETE STRUCTURES

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Abstract

The use of reinforcing bars placed in drilled holes with epoxy or other bonding materials is commonplace in the area of structural retrofit and in particularly for seismic strengthening. The behavior of these bars, requirements on their placement and embedment, and their design are covered in a variety of documents both within and external to the regulatory environment.

The unique case of reinforcing dowels added to a structure to promote composite action between new and existing concrete elements is usually reference to as interface shear reinforcement. While such dowels may also be subject to external tension or compression depending on the geometry and loading of the interface, it is generally assumed that the dominant loading condition is direct shear at the interface. This assumption would generally apply, e.g., to new on-lay shear walls applied to existing wall elements, topping slabs added to existing concrete floor systems to enhance diaphragm strength, and the addition of infill shear walls to reinforced concrete frames.

Nevertheless, despite the ubiquitous nature of these applications, design requirements for shear dowels are largely undocumented and, in particular, there exists little guidance on their proper specification and installation for typical cases.

In this paper, an overview of post-installed interface shear dowels for typical (seismic) retrofitting conditions is presented. Suggestions for selection, dimensioning, and placement of interface shear dowels are provided based on the authors' extensive experience in seismic retrofitting and experimental investigation of interface shear details under monotonic and cyclic loading.

Keywords: seismic; retrofitting; interface shear; post-installed reinforcement

1. Background

1.1 Post-installed reinforcement

The term "post-installed reinforcement" refers to reinforcing bars secured in holes drilled in hardened concrete. Various bonding materials are used for this purpose, including organic resins and inorganic compounds. The uses of post-installed reinforcement include:

a. extensions of existing structures

b. augmentation of foundations

c. earthquake damage repair

d. seismic strengthening

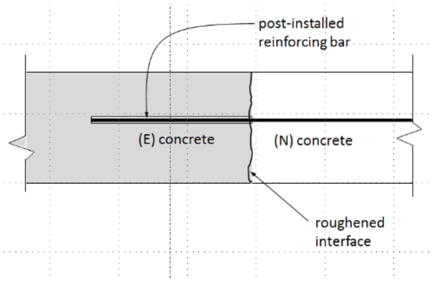


Fig. 1 – Post-installed reinforcing bars

The development of gel adhesives and rapid-cure compounds facilitates the installation of post-installed reinforcing bars in all spatial orientations. Corresponding progress in drilling technology permits the post-installed installation of large diameter reinforcing bars to depths of 60 bar diameters and deeper; however, most applications involve bars of small or medium diameter installed at depths of 10 to 20 bar diameters.

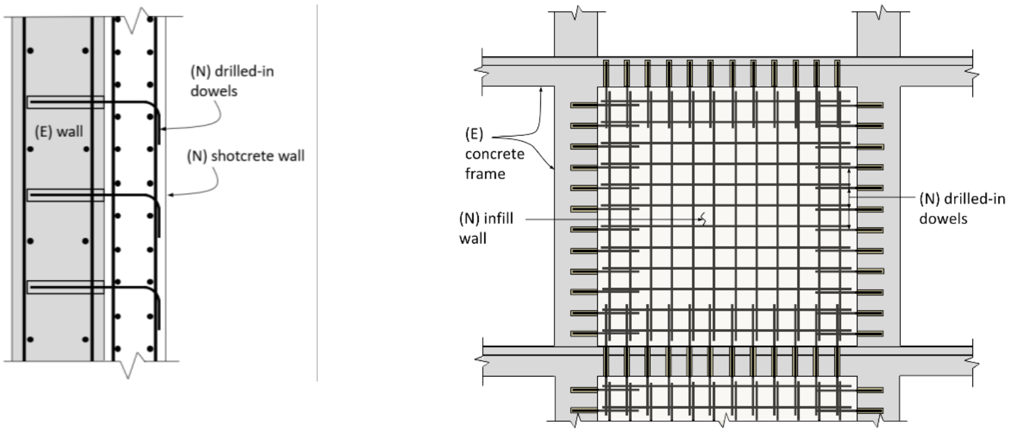
1.2 Applications associated with seismic strengthening

The addition of lateral-load resisting elements to existing reinforced concrete and composite structures such as infill shear walls and collectors as well as the strengthening of existing columns and walls through column jacketing and onlay shear walls all depend on the use of post-installed reinforcing technology. In fact, most seismic strengthening techniques involve some form of post-installed anchorage. The most common use for post-installed reinforcing in this context is the transfer of shear forces. Two notable examples are addressed here.

1.2.1 Onlay shear walls

Existing reinforced concrete walls with inadequate reinforcement and/or poor concrete strength can be enhanced through the application of a new onlay shear wall (Fig. 2a). These are typically constructed with pneumatically placed concrete (shotcrete) and hooked dowels embedded in the face of the existing wall.

The ability of the existing and new walls to act in concert over several cycles of imposed lateral loading is dependent on these dowels. The embedment of the dowels in the existing wall is limited by the wall thickness, and in many cases does not conform to the code-required embedment for full development, i.e., the embedment corresponding to nominal yield of the dowel steel.



(a) (b)

Fig. 2 – (a) Seismic strengthening with an onlay shear wall; (b) Frame retrofit with infill shear walls

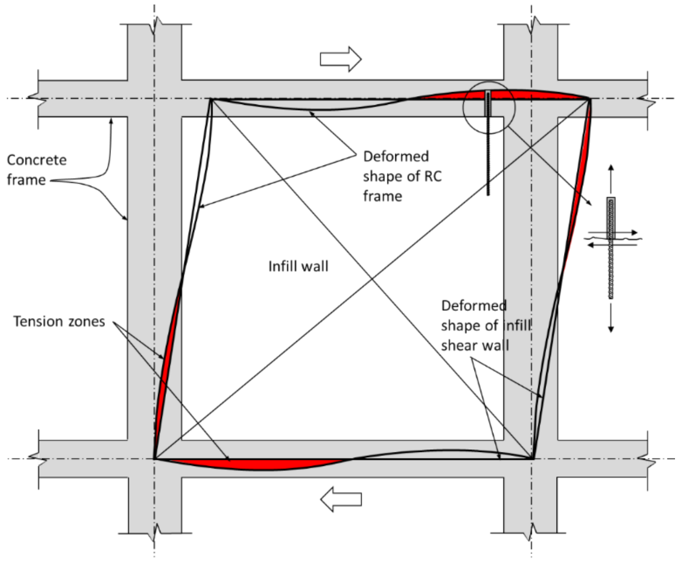


Fig. 3 – Demands on perimeter dowels

1.2.2 Infill shear walls

Infill shear walls are a common approach to the stabilization of nonductile reinforced concrete frames. The effectiveness of this intervention method is almost entirely dependent on the efficiency of the shear transfer around the perimeter of the new infill wall as shown in Fig. 2b. The perimeter dowels will be subject to cyclic shear and, potentially, large displacements. Deterioration of the shear interface may lead to shear failure at the top of the adjacent columns and subsequent deterioration of the vertical load carrying system. The mis-match between the frame deformation and the shear deformation of the infill wall generates additional demands on the dowels (see Fig. 3).

1.3 Current design approach

In the absence of more sophisticated analyses, the typical approach for the design of the dowels in these cases is to divide the total shear by the number of dowels provided. The shear capacity of the dowel is taken as the nominal yield strength of the reinforcing bar times a modification factor associated with the roughness of the interface. The requirement on the dowel embedment is the embedment required to develop the nominal yield strength of the dowel. Where this level of embedment cannot be achieved for the diameter of dowel intended, smaller dowels are used.

1.4 Need for a new model

The accurate prediction of interface shear strength requires a comprehensive understanding of the interaction between the various mechanisms that contribute to resistance across the full displacement range, including adhesive, friction (micro-interlock), and dowel action. Ideally, an understanding of the complete shear slip-response relationship is desired.

2. Interface shear research

The following describes work on interface shear conducted at the National Technical University of Athens (NTUA).

2.1 Database

The literature contains many tests of reinforced interfaces between old and new concrete. An exhaustive review and compilation of the available test record on interface shear was conducted at NTUA. Results from a total of 52 papers published between 1960 and 2019were reviewed. The database includes test results from approximately 800 tests and covers a wide range of parameters. The material strengths (concrete and reinforcement) vary significantly, the dimensions of the interface surface range from 0.032m^2 up to 0.36m^2, while also the interface reinforcement consists of different materials, anchored to the surrounding concrete using different techniques and anchoring methods. In the vast majority of tests, cast-in reinforcement in the form of long straight bars or closed hoops was used.

In contrast, the commonly occurring case of reinforcing dowel bars post-installed in existing concrete with limited embedment is examined in only a limited number of research programs ([1-4]). The most extensive research, performed by Randl [2], addresses monotonic loading of the interface. In that testing program, performed with artificially roughened interfaces, a principal observation was the brittle behavior resulting from concrete cone breakout or pry-out failures. Bass et al., [1], conducted tests on interfaces subjected to cyclic shear displacements (±2.5mm). The embedment length of the 19mm bars crossing the interface was equal to 4d_b (in two specimens), 8d_b, or 12d_b (d_b being the diameter of the bars). Although the authors do not describe the observed failure modes, they comment on the lower shear resistance of the interfaces crossed by shallow bars (-30%). Randl [2] tested monotonically interfaces crossed by 6mm, 12mm, or 20mm post-installed rebars. In case of rebars with embedment length equal to 5d_b, concrete cone failure was observed. Valluvan et al. [3] tested cyclically interfaces crossed by 19mm post-installed rebars with an embedment length equal to 8d_b. When the compressive strength of the existing concrete was low (12 MPa), the failure was concrete breakout. Finally, Hattori and Yamamoto [4] tested interfaces crossed by 19mm, 16mm, or 22mm post-installed reinforcing bars. The embedment length of the bars was equal to 7d_b, 8d_b, 9d_b, or 10d_b. Most of the specimens (19mm rebars embedded 7d_b and 9d_b and 22mm rebars embedded 8d_b) exhibited a concrete-related failure mode.

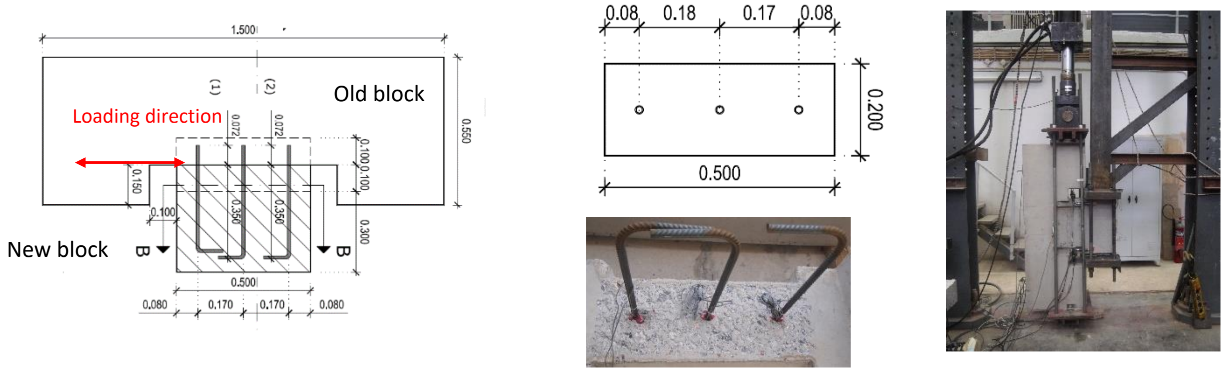
The available experimental results being clear but of limited scope, the decision was taken to further investigate the effect of embedment length of post-installed reinforcing bars on the failure mode and the overall behavior of interfaces.

2.2 Tests at NTUA

The results of the tests performed at the NTUA Laboratory of Reinforced Concrete on the cyclic behavior of interfaces reinforced with post-installed reinforcing bars are described in detail elsewhere ([5, 6]). A summary of the results of the experimental investigations is presented here, emphasizing on the interface failure modes, the magnitude of the interface resistance and its relation to the embedment length of the bars.

The specimens were designed to simulate cold joints (new concrete cast against hardened concrete)and consisted of two reinforced concrete blocks cast approximately 28 days apart. Prior to casting the second block, surface roughening was accomplished with a chiseling tool and the resulting roughness was measured with the sand-patch method ([7]). Three conventional reinforcing bar dowels (nominal 12mm or 16mm) provided with a 90-degree hook on the free end were then embedded perpendicular to the roughened surface in hammer-drilled holes arrayed linearly along the interface (Fig.4a and 4b). A widely available proprietary injection mortar was used to secure the dowels. The projection of the bars above the roughened surface was 350mm. This was deemed sufficient for full development of the hooked end of the dowel, ensuring that the behavior of the interface would be governed by the anchorage of the post-installed (straight) end of the dowel. The casting of the second block then followed, producing an interface with dimensions 200mm x 500mm. The specimens and loading system were uniquely designed to apply cyclic shear displacements across the interface with no eccentricity. Secondary reinforcement was provided at both parts of the specimen, in order to avoid cracks not related to the interface.

The test setup is shown in Fig. 4c([6]). The test rig imposed shear displacements on the specimens at uniform slip rates; three cycles were executed at each displacement amplitude value, each cycle taking approximately 10-15 minutes. Shear slip along the interface was measured by four displacement transducers (two on each face of the specimen), placed in close proximity of the interface, whereas in total four or six displacement transducers placed perpendicular to the interface measured the width of the crack at the interface. In addition, two electrical strain gauges glued on each reinforcing bar were used to measure the strains developed in the dowels during the test. The strain gauges were positioned close to the interface, at a distance of approximately 1.5d_b, oriented along the direction of loading.



(a) (b) (c)

Fig. 4- (a) Geometry of specimens (b) Interface reinforcement and photo of roughened interface, with the reinforcement positioned, before concreting the block simulating the new part of concrete (c) Test setup and specimen in testing position

2.2.1 General observations

In all tests, a crack was observed to open along the interface. This crack was visible even at imposed shear slip values as small as 0.10mm.

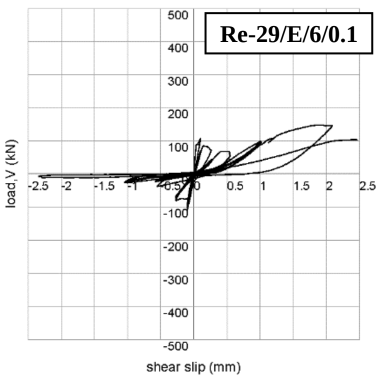
An unfavorable failure mode was observed in specimens with very shallow dowel embedment (6d_b). In such cases, following the initial crack formation along the interface, a second crack opened parallel to the first and on a plane approximately even with the embedded ends of the dowels. This occurred at relatively small imposed displacements(~0.20mm).The development of the second crack, which is assumed to represent tension breakout of the dowels, generally led to precipitous loss of interface shear capacity. This failure mode occurred even with a normal force applied across the interface, albeit at larger slip values (0.30-0.40mm).

In specimens equipped with dowel bars having marginally deeper embedments ($8d_b$ or $10d_b$), the formation of the breakout crack occurred at larger values of imposed displacement (0.40-0.6mm) or was avoided altogether. Furthermore, when such cracking was observed, it was not associated with a concurrent loss of interface shear resistance.

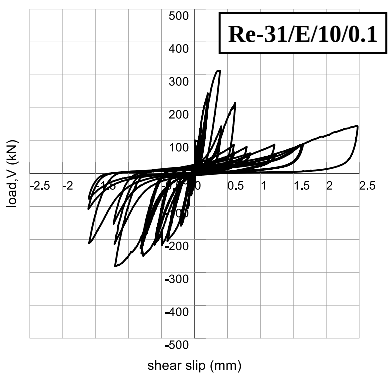
2.2.2 Hysteresis loops and maximum shear resistance

Typical hysteresis loops are shown in Fig.5 and Fig.6. All features that are typical for shear sensitive elements may be observed, namely, pronounced pinching effect associated with limited area of the hysteresis loops and substantial force-response degradation due to cycling.

All tested interfaces had nearly the same concrete compressive strength, and all of them were roughened, having different degrees of roughness. Variations in behavior were associated only with the percentage of the interface reinforcement and the embedment of the dowel bars. It is evident that interfaces reinforced with bars having deeper embedment ($10d_b$ for the 12mm bars and either $8d_b$or $10d_b$ for the 16mm bars) exhibited an enhanced response in terms of maximum capacity compared to those specimens reinforced with bars having only $6d_b$embedment. The asymmetry between the two loading directions is not directly connected to the embedment of the dowel bars but seems to be more related to the percentage of the reinforcement and the roughness of the interface. It is noted that interfaces reinforced with short bars demonstrated limited hysteresis loop areas, pronounced degradation after peak load and unstable behavior until failure. In contrast, interfaces reinforced with bars embedded $8d_b$ or $10d_b$exhibited a more stable behavior and, although the interface resistance was degraded following the peak load, they were nevertheless able to sustain rather large values of applied shear slip. In addition, interfaces reinforced with short dowel bars mobilized their maximum capacity at very small values of shear slip (e.g. 0.1mm), whereas as the dowel embedment was increased, the shear slip corresponding to the maximum interface resistance increased as well.

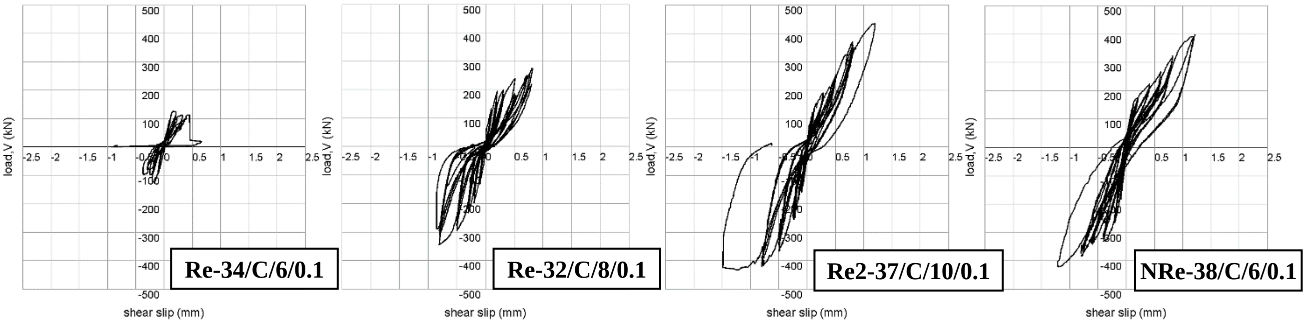


(a)



(b)

Fig. 5- Typical hysteresis loops for specimens reinforced with 12mm bars, having embedment equal to (a) $6d_b$ and (b) 10 d_b.



(a) (b) (c) (d)

Fig. 6- Typical hysteresis loops for specimens reinforced with 16mm bars, having embedment equal to (a) $6d_b$, (b) 8 d_b, (c) 10 d_b, (d) $6d_b$ and compressive stress perpendicular to the interface.

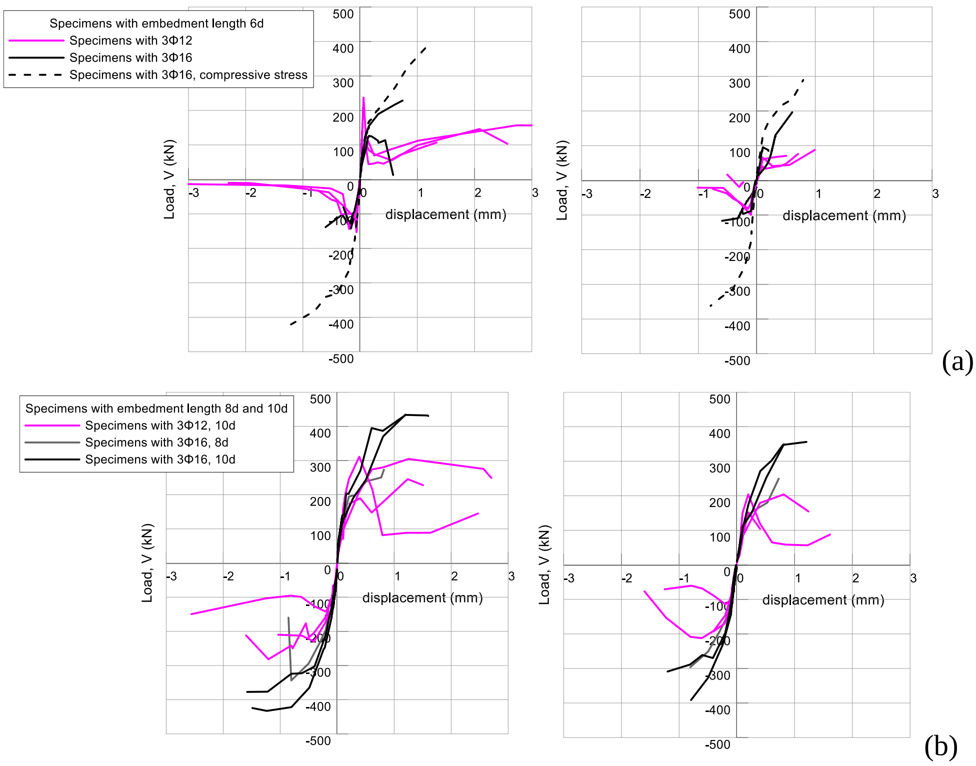


Fig. 7- Hysteresis loop envelopes for specimens with 3Φ12 or 3Φ16 reinforcing bars, with embedment length of the bars (a) $6d_b$ and (b) $8d_b$ or $10d_b$: first cycle and third cycle.

The reduction of the resistance due to cycling is shown in Fig. 8a. The ratio between the maximum response at the second or third cycle to that of the first cycle is plotted against the measured roughness of the interface. It seems that the major parameter affecting the force-response degradation was the dowel embedment, as well as the diameter of the dowel bars. Specimens with larger diameter dowel bars and deeper dowel embedment exhibited a smaller degradation of the interface resistance. On the other hand, there appears to be a dependence of the degradation on the roughness of the interface as well. Considering the value of the shear slip at which the maximum interface resistance is mobilized (Fig. 8b), this value can generally be assumed to be dependent on the diameter of the reinforcement (reinforcement percentage), on the interface roughness, as well as on the embedment of the dowel bars. However, taking into account the observed scatter and the number of tests conducted, a more quantitative assessment is unwarranted.

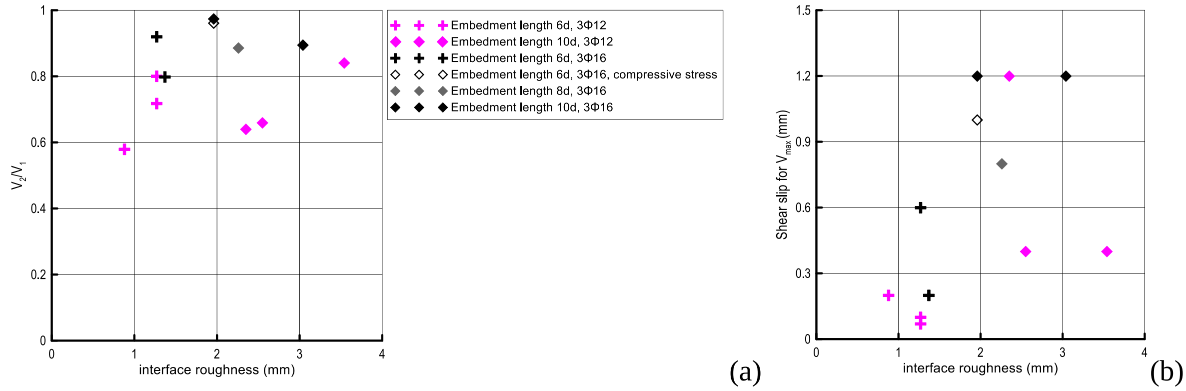


Fig. 8- (a) Reduction of the resistance during cycling, (b) Value of the shear slip at which the maximum interface resistance is mobilized, as a function of the roughness of the interface for various embedment lengths of the post-installed reinforcing bars.

3. Proposed formulation

3.1 Parameters of interest

On the basis of the tests described herein as well as the assembled database, the authors propose a simple and sound physical model capable of describing the behavior of reinforced concrete interfaces under both monotonic and cyclic loading.

Formulations for the calculation of interface resistance are provided in various codes and standards. Nevertheless, these formulations are in many cases deficient in specifying the necessary parameters for an accurate determination of the interface resistance.

For example, in ACI 318 [8], the dowel bars are required to have an embedment corresponding to development of the nominal bar yield stress (so-called development length). In addition, the required depth of surface roughening(~ 6mm) corresponding to a shear value associated with a roughened interface is quite severe.

Eurocode 8, Part 3 [9], dealing with the design of interventions to existing structures, requires the repaired/ strengthened element to behave as monolithic, without providing a method for the calculation.

It is noted that the interfaces between existing and new concrete in case of interventions to existing structures have the following unique characteristics: (a) the interface reinforcement is bonded into the existing concrete using a post-installed reinforcing system and generally anchored by bond or mechanical anchorage in the new concrete; (b) the embedment length, in the existing as well as in the new concrete, depends on the geometry of the existing element and on the intervention technique to be applied. In most cases the embedment length is by necessity rather small, and this may lead to brittle failure modes as discussed in the previous sections; (c) the surface of the existing concrete is often roughened before the application of the new concrete, although roughening of the interface is not always practical and the degree of roughening may be highly variable. Correspondingly, the contribution of the friction mechanism may not be as high as in the case of interface shear across cracks in monolithic concrete.

The main shortcomings of existing formulations for the calculation of interface shear may be summarized as follows: (a) Yielding of the reinforcing dowels is assumed to be a necessary condition. No guidance is provided for cases where dowels have an embedment insufficient to bring the dowel into a tension yielding condition; (b) guidance is lacking regarding the calculation of the interface resistance associated with cycling (e.g., seismic) loading; and (c) the current formulations provide only the maximum interface shear resistance value, without taking into account the value of the shear slip at which the maximum interface resistance is mobilized. This seems at odds with the desire of many codes to move in the direction of performance-based designed methodologies.

3.2 New equation

Although many relationships are proposed in the literature, not all of them are suitable for the purposes of the current investigation given that a) some of the proposed relationships are not general in nature, and b) some relationships require information which is not readily available (tensile strength and unit weight of concrete [10], percentage of the secondary reinforcement parallel to the interface [11], quantified roughness of the interface, R [12]). The relationship proposed by Tassios and Vassilopoulou [13], was identified as superior for the calculation of interface shear and is the basis for the model proposed here and in [14]. This expression adds the contribution of shear resistance to that of dowel action using situation-specific contribution weighting factors. This allows for an accurate prediction of interface shear resistance for many different types of interfaces.

The model of Tassios and Vassilopoulou [13] (Eq. (1)) includes contribution factors which depend on the magnitude of the applied shear slip. This is compatible with the approach taken in the Eurocode 8, Part 3 [9], whereby design of interfaces in repaired or strengthened reinforced concrete elements is carried out for a given performance level and the shear slip imposed on critical interfaces is a function of the design performance level.

$$\tau_u = \beta_d \tau_d + \beta_f \tau_f \qquad (1)$$

where β_d and β_f are the contribution factors for the dowel and the friction mechanism, and τ_d and τ_f are the maximum possible resistances of each mechanism.

The dowel action is taken from the equation (Eq. (2)) proposed by Rasmussen [15]:

$$\tau_d = (1.30 n d_b^2 \sqrt{f_c f_y}) / A_c \text{ (N, mm)} \qquad (2)$$

The contribution factor for the dowel action is considered equal to β_d=0.70. It is though noted that various researchers ([16], [2]), have observed that the minimum embedment of interface shear reinforcing required to develop the maximum shear resistance of the dowel action is $8d_b$. For many strengthening and retrofitting activities, the available concrete depth for interface shear dowels is even less than that required to achieve $8d_b$ embedment. Part of the experiments included in the database and anchored by means of resins, cover this case. For interface shear reinforcing having an embedment length between $8d_b$ and $6d_b$, the contribution of dowel action is taken as 75% of the value assigned for reinforcing embedded $8d_b$ or more, i.e. β_d = 0.7 x 0.75 ~ 0.53. In any case, the contribution of dowel action is in general limited and is associated with small imposed slip values, and/or smooth interfaces, where the contribution of friction is small.

The contribution of the friction mechanism cannot be accurately estimated unless significant parameters, like embedment length of the bars, roughness of the interface, presence of external normal stress, and the type of the interface (natural crack or cold joint), as well as type of loading (monotonic or cyclic) are explicitly addressed.

The friction contribution factor for cold joints is taken as 75% of the value assigned to cracks in monolithic sections, i.e., 0.33 vs. 0.44 in Eq. (3). This reflects the reduced stiffness and strength corresponding to the smoother interface of cold joints, as compared to natural cracks. The total friction contribution is given by Eq. (3) as follows:

$$\tau_f = 0.33 \cdot (f_c^2 \cdot \sigma_c)^{1/3} \text{ (N, mm)} \qquad (3)$$

Where the interface reinforcing is cast-in or installed in drilled holes in the interface and bonded with e.g., a polymer adhesive, as is common in retrofitting applications, the stress to be developed in these reinforcing bars is taken as less than or equal to the nominal bar yield.

The experimental work conducted at NTUA indicates that an embedment equal to $0.80 l_d$ is sufficient to develop the full interface shear resistance, where l_d is the value prescribed by EC2 [17] (Eq. (4)).

$$l_d = \frac{f_y d_b}{4 f_{bu}} = \frac{f_y}{1.89 f_c^{2/3}} d_b \quad \text{(N, mm)} \tag{4}$$

The tensile stress in the dowel bars, and consequently the compressive stress to be developed locally across the interface is therefore calculated using Eq. (5) as follows:

$$\sigma_c = \frac{l_{emb} f_y A_{vf}}{A_c 0.80 l_d} \quad \text{(N, mm)} \tag{5}$$

In case of post-installed dowel reinforcement, the value of τ_{Rd} (bond strength),as determined by qualification testing of the post-installed reinforcement system, is applied in lieu of f_{bu} in Eq. (4).

As already described, testing of interfaces reinforced with post-installed bars having very limited embedment ($6d_b$ to $8d_b$) resulted in sudden failure at maximum slip values (beyond peak resistance) as characterized by concrete cone breakout and subsequent pry-out. Thus, to predict the reduced bearing capacity of interfaces crossed by short bars (embedments between $6d_b$ and $10d_b$), an additional verification for concrete cone breakout capacity is indicated (e.g., according to [18]).

Table 1 – Interfaces between old and new concrete: Contribution factors for the friction mechanism, interfaces with post-installed reinforcement.

Interface Characteristics	**Monotonic Loading**	**Cyclic Loading, Maximum Resistance**		
		$l_{emb}>20d_b$	$12d_b<l_{emb}<20d_b$	$6d_b \le l_{emb} \le 12d_b$
Mechanically roughened (3 mm amplitude), normal strength concrete	0.60	0.60	$0.025\ l_{emb}/d_b + 0.1$	0.40
Mechanically roughened (3 mm amplitude), lightweight concrete or high strength concrete (>C50/60)	0.40	0.40	$0.025\ l_{emb}/d_b - 0.1$	0.20
Smooth Interface	0.40	0.20		
Rough Interface, external compressive stress	0.80	0.80		
Smooth Interface, external compressive stress	0.50	0.50		

The contribution coefficient for the friction mechanism depends on the roughness of the interface, the presence of compressive or tensile stress perpendicular to the interface, and the type of loading (monotonic and cyclic). On the basis of the database assessment, the contribution factors of Table 1 are proposed for the friction mechanism when evaluating the interface resistance of cold joints.

The modified equation (Eq. (1)) along with the additional limitations and verifications, regarding the tensile stress to be developed on the reinforcing bars. were applied to interfaces reinforced with post-installed reinforcement. Given that the aim is the comparison with the experimental results, and not the design of interfaces, mean values of mechanical properties were taken into account. As shown in Fig. 9, the performance of the proposed formula is quite good, and the coefficient of variation is reasonable taking into account the scatter of the experimental results.

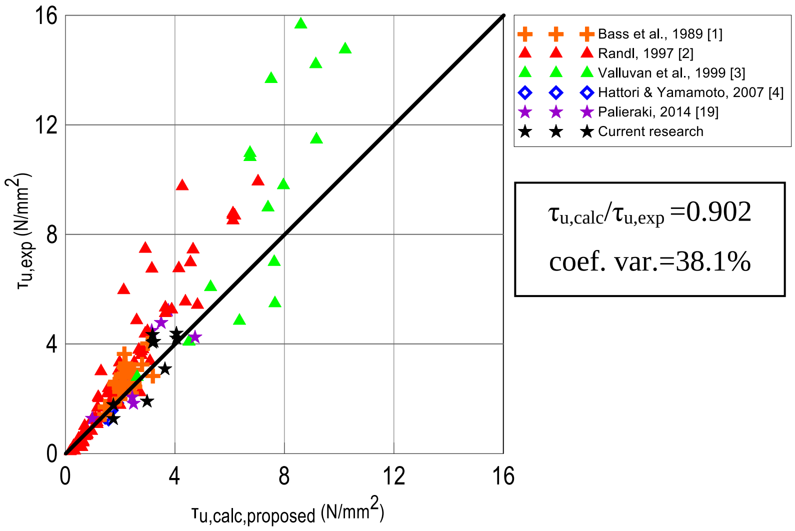


Fig. 9- Interfaces crossed by post-installed reinforcing bars; Comparison between experimental shear resistance and values calculated based on the proposed formula.

4. Conclusions

On the basis of the work presented in this paper, the following conclusions can be drawn:

(1) The use of post-installed reinforcement is very common in different repair techniques. Nevertheless, the guidance for the calculation of the resistance of the interface between concrete cast at different times where post-installed reinforcement is used is lacking in codes and standards, particularly in cases where the embedment of the dowels is limited by the member thickness.

(2) The literature regarding tests on interfaces with post-installed reinforcement is not extensive. Tests performed at the Laboratory of Reinforced Concrete, NTUA have confirmed that the maximum resistance depends strongly on the embedment length of the post-installed end of the dowels. Embedment depths of 6 times the bar diameter lead to sudden concrete breakout failure at small values of imposed shear slip. Increasing the embedment depth to 8 or 10 times the bar diameter improves the behavior.

(3) It is also observed, that even for small imposed slip values (before the occurrence of a concrete failure), the force response degradation due to cycling is more pronounced in case of bars with small embedment length.

(4) On the basis of the tests performed at NTUA, as well as the assembled database, the authors propose a simple and sound physical model capable of describing the behavior of reinforced concrete interfaces under both monotonic and cyclic loading. The performance of the proposed formula is quite good, and the coefficient of variation is reasonable taking into account the scatter of the experimental results.

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