



ALTERNATIVE CONNECTORS FOR SEISMIC INTERFACE SHEAR APPLICATIONS

E. Vintzileou ⁽¹⁾, G. Genesio ⁽²⁾, E. Oikonomopoulou ⁽³⁾, V. Palieraki ⁽⁴⁾

⁽¹⁾ Professor, National Technical University of Athens, elvintz@central.ntua.gr

⁽²⁾ Project Manager, Hilti Corp., Giovacchino.genesio@hilti.com

⁽³⁾ Doctor Candidate, National Technical University of Athens, eratoikonomopoulou@central.ntua.gr

⁽⁴⁾ Sr. Research Engineer, National Technical University of Athens, vasopal@central.ntua.gr

Abstract

Seismic repair and strengthening of existing reinforced concrete structures is a field of growing significance worldwide. Common techniques include the addition of (reinforced) concrete layers to existing members and other shear-dominated connections between structural elements, where proper detailing and design of the interfaces between new and existing concrete is essential to ensure the required shear transfer.

Several design codes (e.g., EN 1998-1) provide guidance on the seismic design of interfaces. These requirements are largely based on shear friction theory. The available design provisions cover cases where reinforcing bars serve as shear dowels crossing the concrete interfaces and, usually, their full anchorage (i.e. length required to reach steel yielding) is assumed in design. Limited or no guidance is provided on the requirements for alternative types of connectors used for this purpose including e.g., screw anchors and post-installed shear lugs. Key differences between such connectors and reinforcing bars include their geometry and load-displacement behaviour, which is strongly related to their load-carrying mechanism (i.e. bond, friction or mechanical interlocking). Furthermore, as with post-installed dowels used for this purpose, embedment as required to develop the strength of the connector in tension is not always feasible (e.g., in the case of thin slab overlays).

In this paper, an overview of alternative post-installed interface shear connectors used in practice is provided. Furthermore, experimental results comparing the performance and behaviour of interfaces crossed by standard reinforcing bars and selected types of alternative connectors are shown and discussed in detail. Finally, proposed requirements for design and specification of such alternative connectors are also presented.

Keywords: Interface shear, Connectors



1. Introduction

The need of connecting reinforced concrete (RC) elements cast at different times to form monolithic elements is of great significance in the construction industry. The range of applications goes from connection of prefabricated RC elements to different strengthening measures of existing structures, e.g., overlays to increase thickness of walls or slabs, jacketing of columns, increase of the static height of beams or connections of infill shear walls to existing framed structures. Despite the large variety of applications, the estimation of the shear resistance at the interface between existing and new concrete can be carried out following the same principles. Several design codes (e.g., [1], [2], [3]) provide guidance on the design of interfaces largely based on shear friction theory, according to which shear is transferred through a combination of friction acting over the interface surface area and dowel action mechanisms. These design provisions typically assume a full anchorage of the dowels intersecting the interface, i.e., their anchorage length is sufficient to allow the interface to reach its full shear resistance without a dowel premature pullout. As dowels, reinforcing bars cast perpendicular or inclined to the interface are typically assumed (see Fig. 1a). It appears evident that several practice relevant aspects of these applications are not taken into account by the currently available design provisions:

- (1) Most of applications (e.g., strengthening measures) require installation of the dowels in the existing reinforced concrete member making a cast-in solution unfeasible;
- (2) In many applications the full anchorage of the connectors is not feasible, e.g., thin overlays for floor strengthening, which typically exhibit thickness lower than 10 cm;
- (3) The use of more engineered types of connectors can be preferred for some applications to improve the productivity on the construction site especially in the case of large applications, e.g., bridge deck and wall strengthening (see Fig. 1b and c);
- (4) In most of the cases, post-installed connectors involving the use of grouts or injected adhesives are used. However, the use of mechanical type of connectors (e.g., concrete screw, see Fig. 4d) might be preferable in some applications because they are easier and faster to be installed, e.g., in overhead applications.

Only recently the European Organization for Technical Assessment has introduced a design Guideline [4], which allows to design of interfaces with connectors embedded with an anchorage length smaller than the one required for a full anchorage and taking into account the properties of engineered connectors in terms of material ductility, cross section geometry and pullout resistance. These design provisions, however, do not cover seismic design.

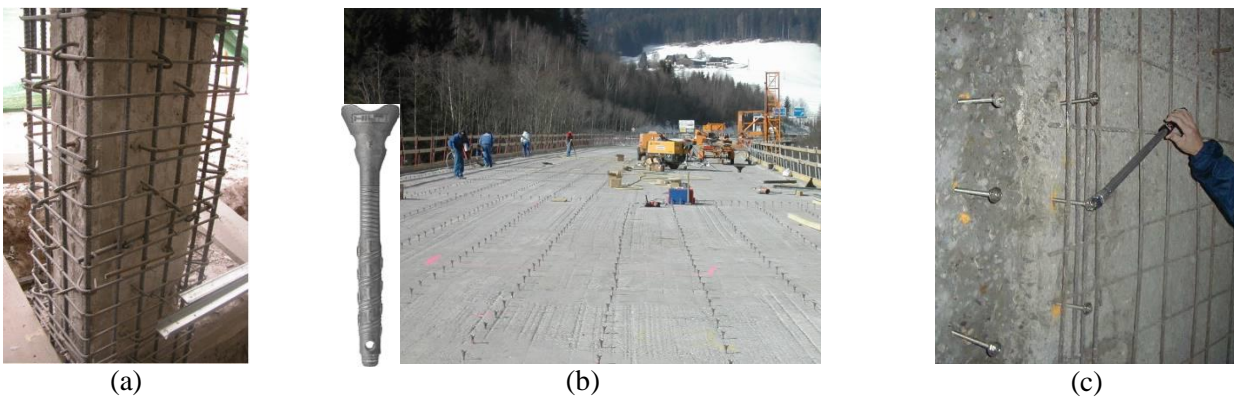


Fig. 1 – Examples of interface shear applications with different types of connectors (a) reinforcing bars, (b) engineered chemical fasteners, (c) threaded rods

In this paper, investigations of the cyclic behaviour of interfaces crossed by different types of connectors are discussed. After a review of results of experimental campaigns available in the literature



(Section 2), the results of tests on interfaces crossed by post-installed reinforced bars and mechanical fasteners (concrete screws) conducted in the laboratory of the National Technical University of Athens (NTUA) are presented (Section 3). Finally, the capability of design equation proposed by [5] in predicting the shear resistance of interfaces involving different types of connectors is shown and discussed (Section 4).

2. Review of types of dowels used for shear-friction interfaces

The published results from tests on reinforced concrete interfaces were compiled to a database created at NTUA. The database collects the results reported in 52 papers published between 1960 and 2019 [6] and is continuously updated. Currently, the database provides information about the behaviour of nearly 1100 tested interfaces including formed and naturally occurring crack surfaces, covering a wide range of material properties, interface geometry, reinforcing ratios and forms of reinforcement. In case of natural cracks, the reinforcement is always in the form of reinforcing bars, positioned before casting the concrete, and therefore anchored by means of bond. In case of cold joints (interfaces between old and new concrete, in total 767 tests), the reinforcement of the interface is usually in the form of cast-in bars or stirrups, anchored by means of bond, or in the form of post-installed reinforcing bars, positioned in the old concrete using adhesives and cast-in the new concrete. Interface reinforcement of other forms has not been extensively studied (Fig. 2, 147 experimental results among 767 tests, ~20%). The use of alternative connectors is more frequent in case of interfaces between steel and concrete ([7], [8], [9], [10]). It is obvious that the behaviour of interfaces between steel and concrete cannot be directly compared to the behaviour of cold joints, given the different materials, the interface roughness as well as the anchorage of the connectors in the metallic part of the interface.

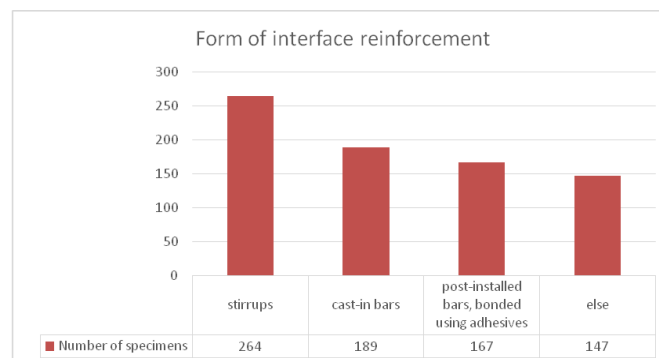


Fig. 2 - Experimental database. Form of the interface reinforcement, in case of cold joints (interfaces between old and new concrete).

The results on interfaces reinforced with connectors different than reinforcing bars (rebars) include powder-driven shear connectors ([11], [12]-Fig. 3a), steel threaded rods [13], steel pipe connection ([14], see Fig. 3b), prestressing rods, used with or without post-installed rebars [15], GFRP bars ([16]-Fig. 3c). Almost all of the tests are monotonic, except than the tests performed by [14] and [15]. The cyclic tests were initially load-controlled, and after reaching the peak capacity or cracking of the interface, they were changed to displacement-controlled.

The most detailed research regards the behaviour of powder-driven shear nails connectors ([11], [12]). It includes 82 tests, 24 among them investigating the interface shear strength of concrete at early ages. The formation of the crack along the interface was followed by the pull-out of the interface reinforcement (nails) from the base plate (existing concrete) or from the overlay (added concrete).

Kamel, 1996 [13] and Shirai et al., 2012 [15] have mainly studied the behaviour of interfaces reinforced with threaded or prestressing rods, where the anchorage is achieved with mechanical means (use of external nuts). Even though the anchorage of the rods is different than the anchorage of reinforcing bars, the strain of the reinforcement and the resulting stress in the concrete was known and could be controlled during testing.



Finally, Alkatan, 2016 [16], has studied the behaviour of interfaces reinforced with GFRP bars, in the form of (a) stirrups, (b) inclined bars or (c) headed bars. Only cracking along the interface was reported in all cases, while also splitting was reported in case of specimens with limited cover of the reinforcement (stirrup-formed GFRP bars).

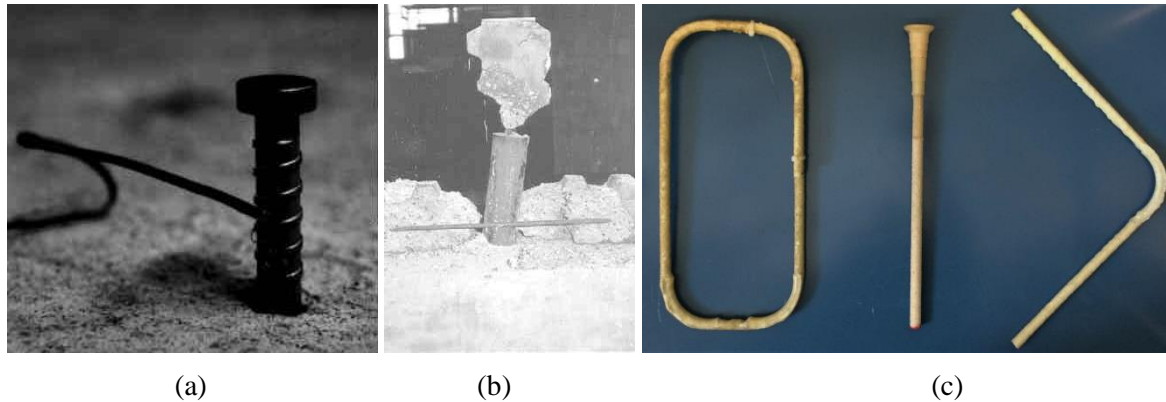


Fig. 3 - Connectors different than reinforcing bars (rebars) used for tests of interfaces: (a) powder-driven shear connectors ([11], [12]), (b) steel pipe connectors, after failure of the interface [14], (c) shapes of GFRP reinforcement [16].

It is concluded that the literature, even though rich in results of tests on reinforced interfaces, does not offer sufficient information regarding the behaviour of interfaces crossed by products different than reinforcing bars. Given the small dimensions of the elements to be reinforced in existing structures, as well as the usually small thickness of the added concrete elements, the need for testing of the anchors used in the everyday practice is obvious. The experimental program performed at the Laboratory of Reinforced Concrete at the National Technical University of Athens (LRC/NTUA) aims at partially covering this lack of information.

3. Experimental validation of alternative dowels

3.1 Experimental Program

The cyclic behaviour of interfaces reinforced with conventional rebars, cast-in [17] or post-installed ([5] and [18]), has been the subject of several experimental campaigns at LRC/NTUA. The results presented herein derive from an experimental campaign focusing on investigating the behaviour of concrete-to-concrete interfaces, reinforced with post-installed alternative connectors and comparing the obtained results with those corresponding to interfaces reinforced with post-installed conventional connectors (i.e., reinforcing bars). The motivation of this study is the evaluation of the potential influence of different products used as connectors on the performance of interfaces.

3.1.1 Description of the specimens and interface reinforcement

As the specimens are designed to simulate interfaces between concretes cast at different times, they are constructed in two distinct phases; the compressive strength of concrete is not a parameter within the present study. The first constructed part corresponds to the old block. After its construction, the surface either remains as cast, against steel formwork, or is manually roughened with a pickaxe and the resulting roughness (Table 1) is measured with the sand patch method [19]. Then, the post-installed dowels are embedded into the old part and, at an age of 28 days approximately, the second concrete block is cast. The resulting interface area is equal to 200*500 [mm] and the geometry of the specimen allows for displacements to be cyclically imposed (Fig. 4a).

Each interface is reinforced with three post-installed dowels, aligned at mid-width of the interface, with the distances between the consecutive dowels and between the dowels and the edges (Fig. 4b) being



The setup used for testing is illustrated in Fig. 4c ([18]). In all tests, there was no external compressive normal stress acting on the interface. Tests were performed under cyclically imposed shear slip at low speed (i.e., quasi-static conditions); three cycles were executed at each displacement amplitude value.

Shear slip along the interface is measured by means of four displacement transducers (two per face of the specimen), placed in close proximity of the interface, whereas in total six displacement transducers placed perpendicular to the interface measure the width of the crack at the interface. In addition, two electrical strain gauges glued on each connector are used to measure the strains developed in the dowels during the test. The strain gauges are positioned close to the interface, at a distance of approximately $1.5d$, oriented along the direction of loading.

3.2 Experimental Results

3.2.1 General observations on behaviour and failure modes

The tests have demonstrated that the design of the specimens was conservative enough to avoid any parasitic or premature cracking in locations other than along the interface or its vicinity. In all specimens, a crack opened along the interface between the two concrete blocks and it was visible even for an imposed shear slip as small as 0.10mm.

In general, interfaces reinforced with mechanical fasteners exhibited a more stable behaviour until failure compared to interfaces reinforced with short chemical anchors (6d). More specifically, in all specimens reinforced with diameter 12mm rebars embedded at 6d, after the formation of the crack along the interface, a second crack parallel to it and close to the end of the embedded bars' length was abruptly formed (Fig. 5b) at small values of shear slip (approx. 0.20mm for rough interfaces) and generally led to failure. After the tests, the two parts of the specimens were easily separated, and the imprint of the rebars could be observed in the old part of concrete. With respect to the specimens reinforced with screws in rough or very smooth interfaces, the crack parallel to the interface, within the old part was either not developed or was formed (Fig. 5a) for very high values of shear slip (3.00mm), approximately at the end of the embedment length of the screws. The undesired concrete cone failure occurred only when considering very rough interfaces reinforced with mechanical fasteners (Table 1-first and second row), but still the opening of the parallel crack was comparatively smaller in this case and occurred for relatively high values of slip (0.50-0.60mm).

Regarding rough interfaces reinforced with diameter 12mm rebars provided with longer embedment length (10d), concrete cone failure (i.e. development of a second crack parallel to the interface) was either avoided (Fig. 5c) or delayed, with the parallel crack occurring at shear slip values of 0.40mm approximately. The second crack, wherever created, was of small width, it did not prevent the continuation of testing and allowed for a further increase of the shear resistance.

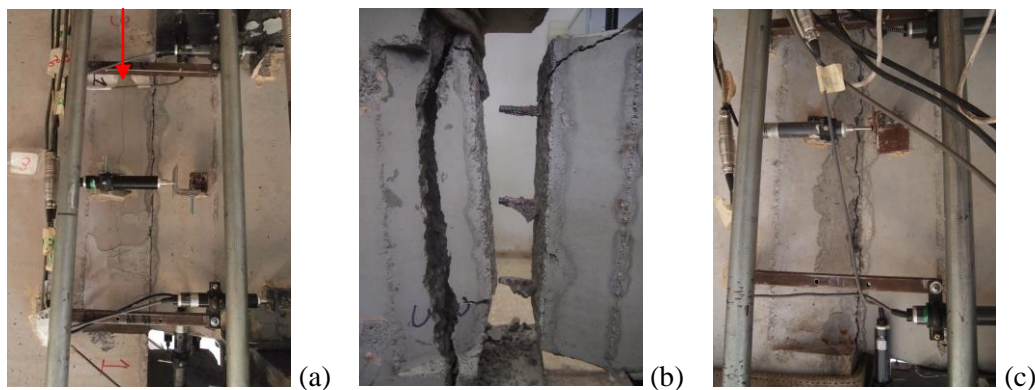


Fig. 5- Failure of rough interfaces after testing. Interface reinforced with (a) concrete screws, (b) diameter 12mm rebars embedded at 6d, (c) diameter 12mm rebars embedded at 10d



Table 1- Summary of experimental results

Specimen name ¹	Connector type	Roughness (mm)	$\tau_{s=0.1mm}$ ² (MPa)	s_{max} ³ (mm)	τ_{max} ⁴ (MPa)	w_{max} ⁵ (mm)	First Crack Parallel to the interface, at s (mm)	Concrete cone failure
R-32/G/65/0.1	Diameter 10mm concrete screws	6.8	0.70	0.50	1.28	1.16	0.50	No
R2-32/G/65/0.1		5.5	0.79	0.85	1.53	1.66	0.60	Yes
R-24/G/65/0.1		1.6	0.58	1.20	1.53	0.91	3.00	Yes
S-25/G/65/0.1		0	0.69	1.70	1.28	0.71	-	No
S-32/G/65/0.1		0	0.27	1.20	0.74	0.58	-	No
Re-29/E/6/0.1	Diameter 12mm rebars embedded at 6d	0.9	1.08	0.10	1.08	0.14	0.20	Yes
Re2-29/E/6/0.1		0.6	1.12	0.07	1.95	0.01	0.20	Yes
Re3-29/E/6/0.1		0.9	0.99	0.10	0.99	0.20	0.20	Yes
ReS-35/E/6/0.1		0	0.70	0.40	0.98	0.27	0.63	Yes
Re-24/E/10/0.1	Diameter 12mm rebars embedded at 10d	2.5	1.09	0.40	2.10	1.66	0.40	No
Re-31/E/10/0.1		1.8	1.20	0.40	2.60	0.54	-	No
Re2-31/E/10/0.1		1.7	1.06	1.20	2.04	1.25	-	No

¹ **Re**: anchorage by means of epoxy resins at rough interface, **ReS**: anchorage by means of epoxy resins at smooth interface, **R**: mechanical anchorage at rough interface, **S**: mechanical anchorage at smooth interface. The first number indicates the compressive strength of the weaker concrete block in MPa
² **E**: specimens with three diameter 12 mm bars, **G**: specimens with three diameter 10 mm screw anchors. The second number indicates: (a) the embedment depth normalized to the bar diameter for the rebars (b) the embedment length in the new part in mm, for the screws.
³ The third number indicates the magnitude of the shear slip imposed in the first set of cycles in mm.
⁴ shear resistance for shear slip equal to 0.1mm, given as the average value between the two loading directions for the first cycle.
⁵ shear slip value corresponding to the mobilization of the maximum capacity of the interface τ_{max}
⁶ maximum shear resistance of the interface, given as the average value between the two loading directions for the first cycle.
⁷ interface crack opening corresponding to the mobilization of the maximum capacity of the interface τ_{max} . The average value between the two loading directions for the first cycle is given.

3.2.2 Observations deriving from the hysteresis loops

Typical hysteresis loops for indicative cases (Fig. 6, Fig. 7) and the hysteresis loop envelopes (Fig. 8a) are given herein, together with the key results of the tested specimens (Table 1). Features typical for shear sensitive elements, as pronounced pinching effect associated with substantial force-response degradation due to cycling, may be observed. It is clear that the behaviour of the interfaces varies significantly depending on the parameters investigated, namely (a) the characteristics of the interface reinforcement and (b) the interface roughness.

Effect of the type of connector

For similar roughnesses of differently reinforced interfaces, it is evident that interfaces reinforced with screws (Fig. 6b and Fig. 7a) exhibit an enhanced response in terms of maximum capacity compared to those reinforced with bars of similar embedment length (6d-Fig. 6c and Fig. 7b) for rough and smooth interfaces, respectively. Interfaces reinforced with screws are also characterized by a rather stable post-peak behaviour with moderate degradation due to cycling, as illustrated in the envelopes (Fig. 8a). However, the asymmetry between the two loading directions is not negligible, especially in case of very rough interfaces (Fig. 6a).



Contrarily, interfaces reinforced with short bars demonstrate limited hysteresis loops area, pronounced degradation after peak and unstable behaviour until failure. However, a more symmetrical response is observed in the two loading directions. In addition, interfaces reinforced with short bars mobilize their maximum capacity at very small values of shear slip (e.g. 0.1mm for the case of roughened interfaces – Table 1), whereas interfaces reinforced with screws mobilize their ultimate response step-wise and are capable of sustaining also larger shear slips, facts that reveal the application-dependence suitability of each connector type.

The positive effect of the increased embedment length feasible with rebars (10d) is clearly illustrated in the hysteresis loop of Fig. 6d, where the maximum resistance is significantly higher compared to the previously described cases. Nevertheless, intense asymmetry in the two loading directions can be observed for large embedment, as well. Although there is scatter in the experimental values of the force response degradation due to cycling, it is clear that, as the embedment length is decreased, the reduction of the resistance becomes more significant (Fig. 8a). As observed for the case of screws, also for interfaces reinforced with long rebars, the mobilization of the maximum capacity is achieved for rather high values of shear slip, whereas the mobilized resistance at $s=0.1\text{mm}$ amplitude during the first set of cycles is half-or even less-of the finally maximum mobilized resistance (at $s\geq 0.40\text{mm}$).

Effect of Interface Roughness

The alternative connectors were tested with different roughnesses of the interface, as presented in Table 1. As the roughness of the interface is reduced, it seems that the resistance is also decreased and the asymmetry is moderated as well. More specifically, the ratio between the response in the two loading directions when maximum resistance is reached (V_{u+}/V_{u-}) varies from values larger than 2 for very rough interfaces (Fig. 6a) to approximately equal to 1.5 for very smooth interfaces (Fig. 7a). In addition, a dependence of the force-response reduction due to cycling on the interface roughness can be detected, with higher roughness leading to intense degradation (Fig. 8a). Indeed, rough interfaces undergo significant deterioration (fracture of protruding aggregates and cement paste) even during the first half of the first loading cycle, leading to significantly smaller response in the second loading direction. As illustrated in Fig. 8b, the shear slip corresponding to the mobilization of the maximum shear response tends to be reduced for an enhanced interface roughness, especially for interfaces reinforced with screws.

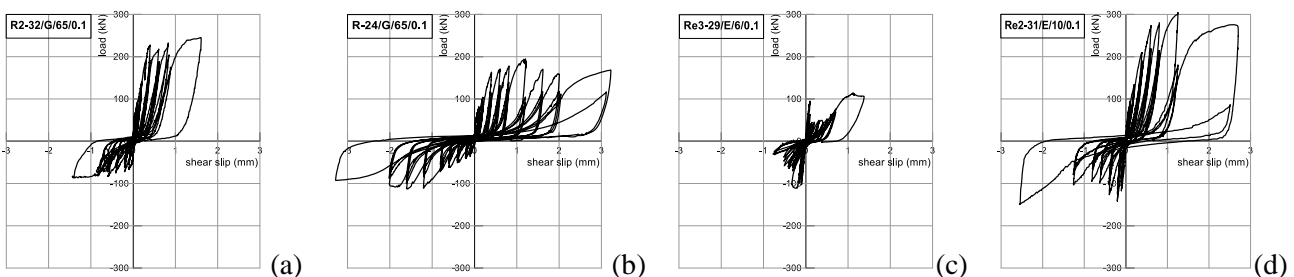


Fig. 6- Hysteresis loops for rough interfaces reinforced with (a) diameter 10mm concrete screws-very rough interface, (b) diameter 10mm concrete screws, (c) diameter 12mm rebars embedded at 6d, (d) diameter 12mm rebars embedded at 10d

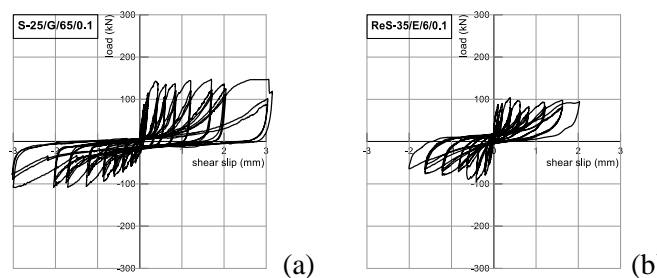


Fig. 7- Hysteresis loops for very smooth interfaces reinforced with (a) diameter 10mm concrete screws, (b) diameter 12mm rebars embedded at 6d

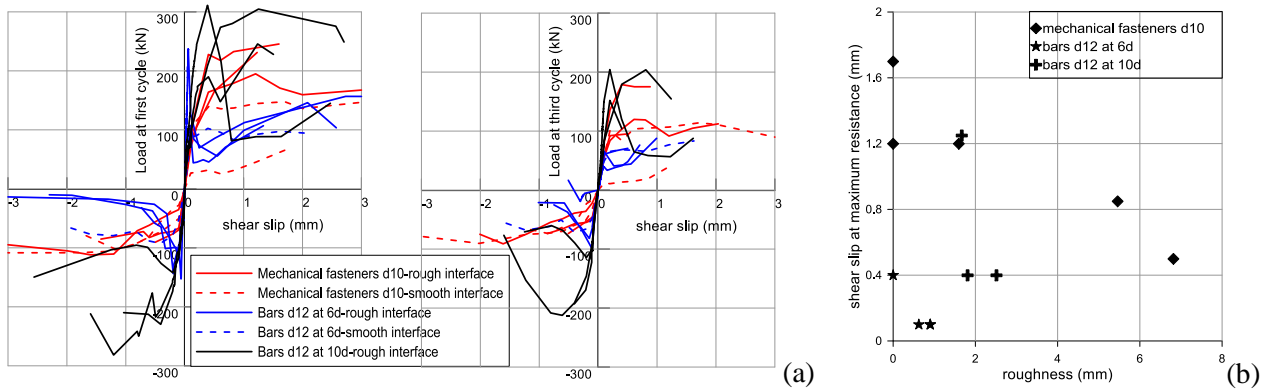


Fig. 8- Diagrams including all examined specimens: (a) Hysteresis loop envelopes for the first and the third cycle, (b) shear slip corresponding to the maximum resistance of the interface (average of the two loading directions) plotted against the measured roughness

3.2.2 Calculation of the maximum shear resistance

Several relationships proposed by investigators (e.g. [21], [22], [23], [24], [25]) or included in current Codes (e.g. [3]) for the calculation of the maximum shear resistance of concrete interfaces crossed by reinforcement, do not seem to be adequate for the calculation of the resistance of interfaces between old and new concrete reinforced with alternative connectors. Most of the proposed equations assumes yielding of the reinforcement, and do not consider possible failure modes, such as concrete cone failure or pullout of the dowels, where a full anchorage is not feasible. The Eq. (1), presented herein, proposed by the LRC/NTUA team [5], offers the possibility of taking into account (a) the different failure modes and (b) tensile stresses of the interface reinforcement smaller than its yield strength, according to the mechanism mobilized for the anchorage as well as the (usually limited) embedment length of the bars.

$$\tau_{Rdi} = \mu \cdot \sigma_n + k_1 \cdot \rho \cdot \sigma_s \cdot (\mu \cdot \sin \alpha + \cos \alpha) + k_2 \cdot \rho \cdot \sqrt{f_{yd} \cdot f_{cd}} \leq \beta_c \cdot v \cdot f_{cd} \quad (1)$$

where, strength values are in N/mm^2 and:

μ is the friction coefficient;

σ_n is the (lowest expected) compressive stress resulting from an eventual normal force acting on the interface;

k_1 is the interaction coefficient for tensile force activated in the reinforcement or the dowels;

ρ is the reinforcement ratio of the reinforcing steel crossing the interface;

σ_s is the tensile stress of the (insufficiently anchored) reinforcement crossing the interface;

α is the inclination of the reinforcement crossing the interface;

k_2 is the interaction coefficient for flexural resistance;

β_c is the coefficient for the strength of the compression strut; and

$$v = 0.55 \left(\frac{30}{f_{ck}} \right)^{1/3} < 0.55$$

The factors expressing the contribution of each mechanism to the shear resistance of the interface, k_1 and k_2 , are described in detail in [5]. The contribution factors depend on the roughness of the interface, the embedment length of the anchors, the type of loading (monotonic or cyclic) and the presence of an external compressive stress acting perpendicular to the interface.

It is noted that in Eq. (1) the friction coefficient, μ , is not expressed by a constant value. It is well known that the friction coefficient is a function of the ratio between the normal stress on the interface and the compressive strength of the weaker concrete. Thus, the following Eq. (2) applies:



$$\mu = 0.33 \cdot \sqrt[3]{\left(\frac{f_c}{(\sigma_c + \sigma_n)}\right)^2} \quad (2)$$

As already mentioned, the validity of Eq. (1) depends on the anchorage conditions of the reinforcement crossing the interface. When a bar is anchored to the concrete by bond (usually in the new concrete) or by use of resins or mechanical anchorage (usually in the old concrete) and its embedment length, l_{emb} , is smaller than the required for full anchorage, the maximum tensile stress, σ_s , to be developed (obviously, smaller than the yield strength of the bar) is inserted in Eq. (1) for the calculation of the friction component. It can be calculated and translated into compressive stress on the concrete, σ_c . The following Eq. (3) applies:

$$\sigma_c = \frac{l_{emb} f_y A_s}{A_c 0.80 l_b} = \rho \cdot \sigma_s \quad (\text{N, mm}) \quad (3)$$

where, l_b denotes the anchorage length, according to EN 1992-1-1 (2009), $l_b = (f_{yd} \cdot d)/4f_{bd}$

As previously described, interfaces reinforced with post-installed reinforcing bars or anchors, embedded in the old concrete to a limited depth (6 to 8 times the bar diameter), exhibited quite frequently brittle failures, namely, concrete cone breakout and pull-out failure. Thus, to predict the (reduced) bearing capacity of interfaces crossed by short post-installed bars (embedment length between 6d and 8d), an additional verification (on top of Eq. (3)) regarding the decisive failure mode of the connectors is required (e.g., steel yielding, pullout or concrete cone breakout capacity, the last two calculated in accordance with [26]).

The proposed formula was applied to interfaces reinforced with alternative types of connectors, tested at LRC/NTUA, or reported in the Literature, if the bond strength of the reinforcing bar as per [1] is replaced by the pullout strength of the concrete screw or other alternative connector types. Given that the calculated values are used for comparison with experimental results, and not for design purposes, mean values of the mechanical properties of the materials are taken into account. As shown in Fig. 9, the proposed formula can accurately predict the experimental results. The average value of the calculated values divided by the experimental ones is almost equal to the unity, while also the coefficient of variation is quite high, also taking into account the scatter of the experimental results obtained with different test setups.

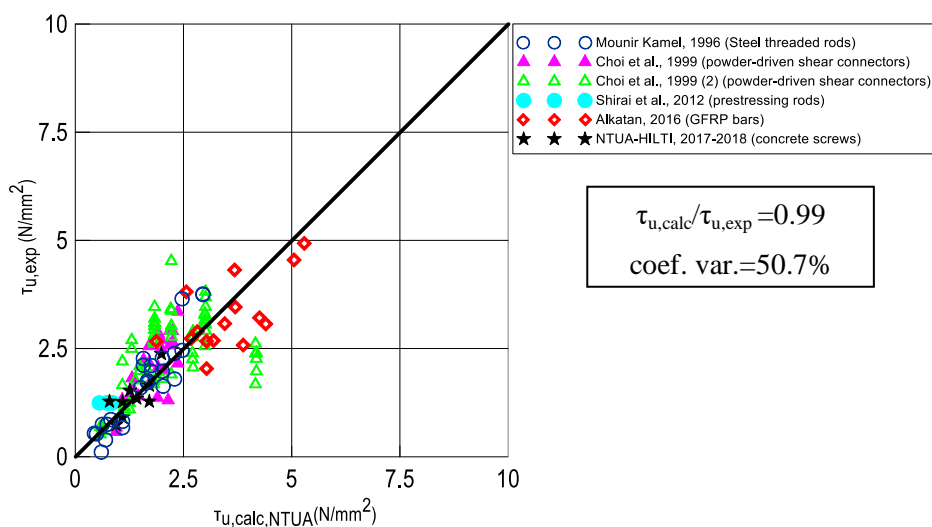


Fig. 9- Comparisons between the proposed equation model with experimental results for specimens with interfaces between the old and the new concrete reinforced with alternative connectors.



4. Summary and Conclusions

The main observation deriving from testing is that the product serving as interface reinforcement plays a critical role on the interface behaviour. The conclusions listed herein are representative of the cyclic behaviour of the tested interfaces which, although rather limited in number, yielded consistent results:

1. An unfavourable behaviour leading to premature and brittle failure for specimens with diameter 12mm rebars having a short embedment length (6d) into the old part of concrete was systematically recorded. Such an unfavourable failure mode seems to indicate that an embedment length equal to 6d might not be recommended in design. On the contrary, specimens with screws and specimens with rebars of larger embedment length (10d) did not experience such an unfavourable failure mode and consequent brittle behaviour.
2. For the same level of roughness, the shear slip corresponding to the maximum capacity reaches higher values for interfaces reinforced with mechanical fasteners, instead of short rebars, whereas the values of maximum resistance are slightly higher for the interfaces reinforced with screws. The use of mechanical fasteners induced a more intense asymmetry in the resistance of the interface between the two loading directions, compared to the interfaces reinforced with short bars, but demonstrated a more stable post-peak behaviour and withstood higher values of shear slip while degrading.
3. As the roughness is decreased, the interface exhibits lower shear resistance. However, smaller roughness leads to less pronounced force-response degradation, as well as limited asymmetry of resistance between the two loading directions.
4. The design equation proposed by [5] is capable to predict the resistance of shear-friction interfaces crossed by reinforcing bars as well as alternative connector types with embedments not sufficient for a full anchorage, which is a common situation in practical applications.

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