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SHEAR TRANSFER ALONG INTERFACES: CONSTITUTIVE LAWS

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ABSTRACT

This paper presents constitutive laws adequate for predicting the maximum shear load that can be transferred along reinforced concrete interfaces subjected to monotonically or cyclically imposed displacements. A previous empirical formula is modified with the purpose to reach reliable prediction of the maximum resistance of various types of reinforced concrete interfaces. The application of the modified formula to 580 experimental results from the literature proves the adequacy of the proposed laws.

INTRODUCTION

In various repair and/or strengthening techniques, in case that the intervention consists in adding a new concrete layer or new RC elements to the existing members of the structure, the connection between the new and the old concrete has to be adequately designed and detailed. Various techniques suggested and used in construction, aim to establish a better connection between the two different layers, so that the resulting, composite, element behaves as monolithic. Nevertheless, the shear load to be transferred along the interfaces, depends on the means of connecting the old and the added concrete (use of reinforcing bars or anchors, acting as dowels, roughening of the old concrete surface before casting the new layer) and it is a function of the shear slip along interfaces, a prerequisite for the mobilization of the resistance at the interface. In case of structures subjected to earthquakes, the behaviour of interfaces may become critical for the overall behaviour of the structure, due to substantial degradation of the resistance of the interface under cyclic actions.

On the other hand, in the design of an interface crossed by reinforcing bars or by anchors, one cannot additively superimpose the maximum resistance offered by the two main mechanisms (shear friction and dowel action). The interaction between the two mechanisms has to be taken into account, along with the fact that their maximum resistance is not mobilized for the same value of shear slip.

Although, the behaviour of interfaces was experimentally investigated in numerous studies, the available information is not sufficient for the design of interfaces in the case of RC structures subjected to earthquake excitations. An experimental campaign was carried out at the Laboratory of RC, NTUA, for the systematic investigation of RC interfaces within repaired or strengthened elements. Among the aims of the experimental investigation is also the proposal of constitutive laws for the accurate prevision of the interface resistance and overall behavior.

In the present paper a summary of the available experimental results is presented, as well as the results of a study that was undertaken with the aim to predict the maximum resistance of RC interfaces under imposed monotonic or cyclic excitation.

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LITERATURE SURVEY

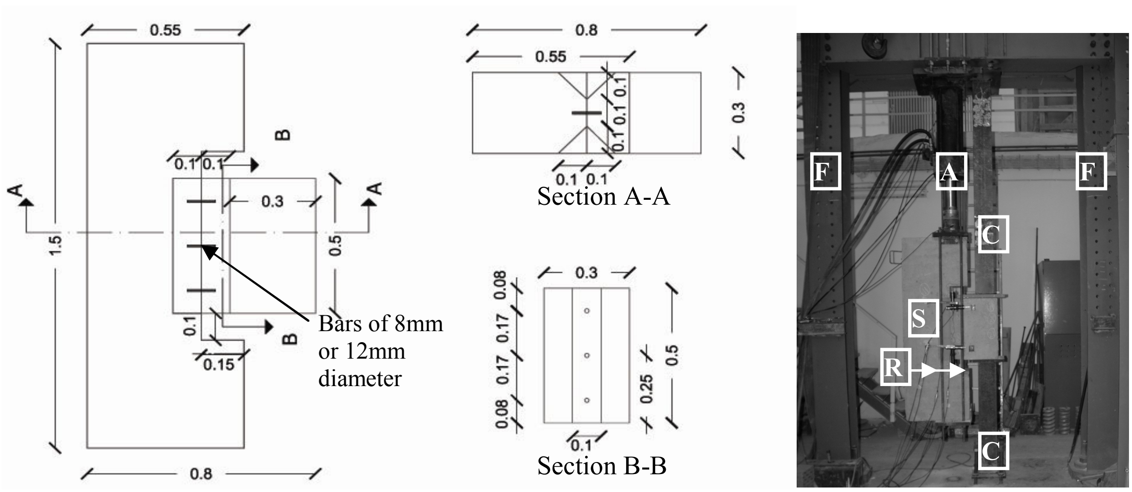
The results of numerous tests on (plain or reinforced) concrete interfaces are reported in the international literature. Tests simulate various cases of interfaces, such as construction joints, connections between precast elements, natural cracks, etc. In most of the tests, interfaces were subjected to monotonically increasing load up to failure. Data regarding the behaviour of reinforced interfaces simulating the interfaces between old and new concrete in repaired/strengthened elements, subjected to cyclic shear slip are rather scarce. The experimental research carried out by the authors, mainly aims at covering the lack of results regarding the cyclic behavior of interfaces between old and new concrete, in repaired or strengthened elements.

The number of tests performed at NTUA (43 tests on specimens subjected to cyclic shear slip, Palieraki, 2014) allow for conclusions regarding the behavior of interfaces in cyclic shear to be drawn. Nevertheless, it is obvious that the tests do not cover the wide range of the parameters influencing the behavior of the interfaces, e.g., the mechanical characteristics of concrete and steel. In order to formulate a constitutive law, which could be generally applied, experimental results from the literature are re-evaluated.

Tests regarding the behavior of interfaces are performed using (a) specimens in the form of beams, strengthened using added concrete, tested in 3-point bending, causing indirect shear of the interface, (b) monolithic specimens, tested as constructed, or cracked before being tested, (c) specimens constructed in two consecutive phases, simulating interfaces between new and old concrete, as are the specimens tested by the authors, and finally (d) specimens having two interfaces, simulating connections between precast concrete elements. In some of the specimens, compressive or tensile stress is applied perpendicularly to the interface. The percentage of the reinforcement crossing the interface varies between 0.014% and 4%, while the most frequently used percentages are in the range of 0.5% to 2%.

The different test setups used in order to perform the tests have some common characteristics, but may present significant differences, depending on how the interface is constructed (in one or two phases) and according to the purpose of the investigation. One of the most commonly used test setups is similar to the one used at NTUA (Fig.1).

Given that different kinds of test setups can be found in the literature, leading to different results, not directly comparable in several cases, and given the particular interest of interfaces between old and new concrete, attention has been paid to the aforementioned cases of interfaces. In total, results from 18 papers, produced between 1960 and 2012 have been collected. Results from almost 580 tests regarding interfaces with different dimensions and geometry, covering a wide range of material properties are included in the evaluated research works.



(a) (b)

Figure 1. Tests at NTUA: (a) Geometry of the specimens with three bars crossing the interface (dimensions in meters), (b) Photo of the test set up, with specimen in the testing position.

MAXIMUM INTERFACE RESISTANCE-INFLUENCE OF SIGNIFICANT PARAMETERES

The available experimental results reported in the literature have been re-evaluated and assessed in relation to significant parameters, which, as generally admitted, affect the behavior of interfaces. Shear is transferred along the interfaces mobilizing the mechanism of concrete to concrete friction and the dowel action of the bars crossing the interface. The main parameters under investigation are the compressive strength of concrete, the number and the diameter of the bars crossing the interface, the anchorage length of the bars crossing the interface, and the presence of compressive or tensile stress, acting perpendicularly to the interface. Given that in the present paper the resistance of interfaces between old and new concrete is investigated, the specimens usually consist of two parts, constructed separately. The smaller compressive strength of the concrete of the two parts of the specimens is the one that governs the resistance of the interface. The parameters related to the percentage of the reinforcement crossing the interface, can be unified in one parameter, ρf_y (where "ρ" denotes the percentage of reinforcement and "f_y" denotes the yield strength of the bars), which corresponds to the maximum compressive stress which can act on the concrete interface, because of the tensile stresses to be developed in the reinforcing bars of the interface. In the parameter, the small anchorage length of the bars can be taken into account, given that for smaller length the tensile stress in the bars is considered to be reduced. Additionally, in the parameter ρf_y, the external compressive or tensile stress, acting to the interface is added or subtracted accordingly.

As long as it regards the embedment length, it is taken into account as follows: Most of the specimens are reinforced with bars in the form of closed loops. The bars in this case, are considered to be sufficiently anchored, and able to develop their yield strength. The bars anchored by means of resins are also considered to be able to develop their yielding stress. In the case of bars anchored to the concrete by means of bond, having a small embedment length, the stress to be developed in the bars is considered to be smaller than their yielding stress. The tensile stress in the bars, and consequently the compressive stress to be developed in the concrete can be calculated according to Eq. (1):

$$\sigma_c = \frac{l_{emb} f_y A_s}{A_c 0.80 l_b} \quad \text{(N, mm)} \tag{1}$$

In Eq. (1), the embedment length that is necessary for the bars to develop their yield strength is taken equal to 80% that prescribed by EC2 (Eq. (2)). This is because, the experimental results obtained at NTUA (Vintzileou and Palieraki, 2007, Palieraki and Vintzileou, 2009, Zeris et al., 2011, Palieraki, 2014) have shown that embedment length equal to $0.80l_b$ is sufficient for the full anchorage of bars used for the reinforcement of interfaces subjected to shear.

$$l_b = \frac{f_{yd}\Phi}{4 f_{bu}} \quad \text{(N, mm)} \tag{2}$$

The effect of the main parameters on the maximum resistance of interfaces is shown in Fig. 2: The resistance of the interface is plotted against the least of the two compressive strengths, as well as against the values of the parameter "ρf_y". In addition, to make the effect of the compressive strength of concrete more evident, the shear resistance values are reported to the parameter "ρf_y".

The diagrams for the specimens simulating interfaces between old and new concrete clearly show that the reinforcement parameter is the one governing the resistance along the interface. The increase of the reinforcement percentage leads to an increase of the interface resistance. The influence of the concrete compressive strength is not so clear. For normal concrete compressive strength, up to 60.00MPa, the increase of the concrete strength leads to an increase of the interface resistance. This trend is not clear for higher values of the compressive strength of concrete. In case of interfaces formed within a monolithic element, cracked before testing the interface, this feature can be attributed to the fact that a crack in high strength concrete crosses not only the cement matrix, but also the aggregates, leading to a smoother interface. In the case of interfaces between old and new concrete, this could be also attributed to the different roughness of the interface.

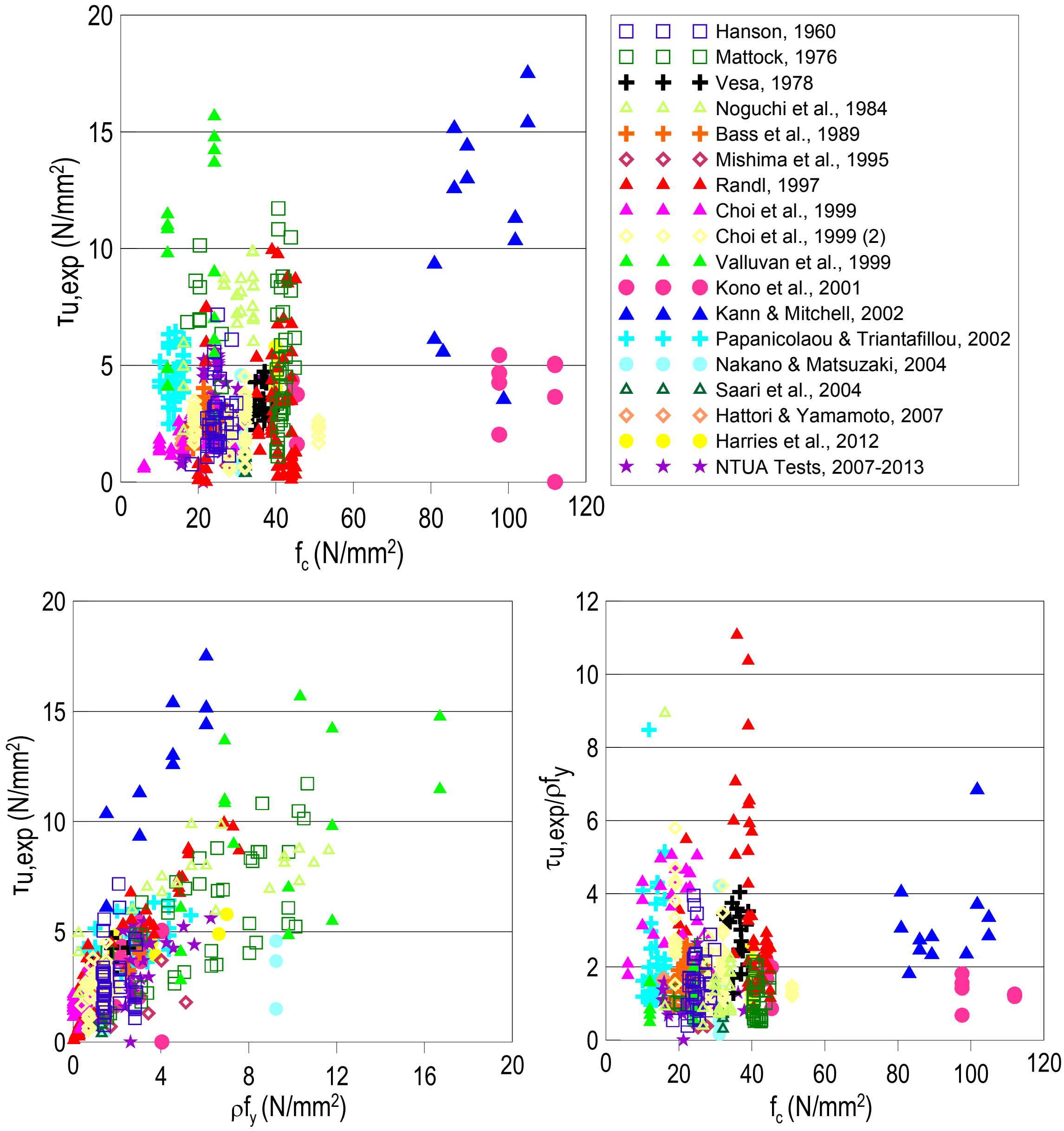


Figure 2. The effect of the least concrete compressive strength and the reinforcement parameter, ρf_y, on the shear resistance of interfaces between old and new concrete.

PREDICTION OF THE MAXIMUM INTERFACE RESISTANCE-AVAILABLE RELATIONSHIPS

In the literature, as well as in some Codes, several relationships are given for the prediction of the maximum interface resistance. Those relationships cannot always be applied in the case of interfaces between old and new concrete, in repaired/strengthened elements, because of the specific characteristics of the abovementioned interfaces: The quality and the strength of the new and the old concrete may differ significantly. The surface of the old concrete may be smooth or roughened, using various techniques. The interface reinforcement is anchored in the old concrete by means of resins or other mechanical means, while in the new concrete, the anchorage of the reinforcement is achieved through bond with the concrete. The dimensions of the old, as well as the added part of concrete, are often small, not allowing for full anchorage of the reinforcement or/and for sufficient distances from the edges of the elements.

Among all the available relationships, those able to predict the shear resistance of interfaces between old and new concrete are used on a large number of experimental data from various sources.

Those relationships were proposed by researchers (Pruijssers, 1988, Tassios and Vassilopoulou, 2003, Harries et al., 2012), or they are included in Codes (ACI 318, 2011 and CEB-fib Model Code 10, 2012).

Equation proposed by Pruijssers (1988), Equ. (3):

$$\tau_u = a(\rho f_y)^b \tag{3}$$

Where: ρ denotes the reinforcement percentage of the interface

f_y denotes the yield strength of the steel

α and b are empirical parameters: $a = 0.822 f_{ccm}^{\ 0.406}$ and $b = 0.159 f_{ccm}^{\ 0.303}$

f_{ccm} denotes the compressive strength of conventional 150mm cubes.

It is noted that the relationship is proposed by Pruijssers (1988) for interfaces within specimens constructed monolithically and cracked before testing.

Equation proposed by Tassios and Vassilopoulou (2003), Equ. (4):

$$\tau_u = \beta_d \tau_d + \beta_f \tau_f \tag{4}$$

Where β_d and β_f are contribution factors for the mechanisms acting along the interface, namely friction (Equ. (5), as proposed by Tassios and Vintzileou, 1987) and dowel action (Equ. (6), as proposed by Rasmussen, 1962). The formula by Rasmussen is valid for dowels provided with concrete cover sufficient for splitting failures to be avoided as described herein:

$$\tau_f = 0.44\sqrt[3]{f_c^2 \sigma_c} \text{ (N, mm)} \tag{5}$$

where: f_c denotes the least compressive strength of concrete

σ_c denotes the compressive stress acting perpendicularly to the interface. The compressive stress may be due to an external acting stress or to the tensile stress of the bars crossing the interface (=ρf_s, f_s denotes the tensile stress of the bars),

$$\tau_d = (1.30 n d_b^2 \sqrt{f_c f_y}) / A_c \text{ (N, mm)} \tag{6}$$

where: n and d_b denote the number and the diameter of the bars crossing the interface.

The contribution factors for the mechanisms acting across the interface (β_d and β_f), were determined by Tassios and Vassilopoulou (2003) on the basis of experimental results obtained from testing each shear transfer mechanism separately (Vintzeleou and Tassios, 1987, Tassios and Vintzileou, 1987) and taking into account the interaction between the two mechanisms. Tassios and Vassilopoulou (2003), have concluded that for slip values not exceeding 0.40mm, the contribution factor of the friction mechanism is equal to 0.40, whereas that of the dowel mechanism is equal to 0.70. For large values of the imposed shear slip (s>2.00mm), the contribution factor of the friction mechanism becomes equal to 0.80, that of the dowel action remaining equal to 0.70. When the value of the imposed slip is not known, or for concrete strength higher than 40.00MPa, Tassios and Vassilopoulou (2003) suggest to use reduced contribution factors, namely 0.70 and 0.60 for friction and dowel action respectively. Given that the values of the imposed shear slip are not known for all the available experimental results, and the concrete strength is for many tests higher than 40.00MPa, for the comparison in the current paper, the contribution factors of 0.70 and 0.60 for friction and dowel action respectively are used.

Equation proposed by Harries et al. (2012), Equ. (7):

$$\tau_u = a f_c + 0.002 \rho E_s \le 0.20 f_c \text{ (N, mm)} \tag{7}$$

where: E_s denotes the elastic modulus of the interface steel reinforcement

α stands for an empirical parameter. The value of the parameter is taken into account according to the type of the specimen under investigation, i.e.:

α= 0.075 for monolithic, uncracked, specimens

α= 0.040 for specimens having a cold joint, constructed in two different phases (the case of interfaces between old and new concrete)

α= 0.000 for specimens cracked before testing

Equ. (7) is a design-oriented equation. Given that the equation is used to predict experimental results, partial safety factors for the materials, namely for concrete and steel, are not used. It has to be admitted though that avoiding the use of safety factors may not be sufficient for a design-oriented equation. Thus, it is expected to lead to resistance values smaller than the experimental ones.It is noted that in Equ. (7), the elastic modulus of the steel crossing the interface is used, instead of its yield strength: According to the tests performed by Harries et al. (2012), and the steel strains measured during testing, Harries et al. (2012) suggest that, in case of high or medium strength steel (f_y>400MPa), the bars do not reach their yield strength.

Equations proposed in Codes:

ACI 318 (2011), equation (Equ. (8)):

$$\tau_u = \mu A_s f_y / A_c \leq min(0.20 f_c, 5.515) \text{ (N, mm)} \quad (8)$$

where: μ denotes the friction coefficient along the interface; a set of values are specified for different interface construction methods, namely,

μ=1.40 for monolithic, cracked or uncracked, specimens

μ=1.00 and μ=0.60 for concrete placed against hardened concrete, for rough or smooth interface of the hardened concrete, respectively.

Equ. (8) is one of the most commonly used equations for the calculation of the interface resistance. It is noted that many researchers, including the authors of this paper, have concluded that the upper limits, suggested by the ACI Code, i.e. the limit of $0.20f_c$ or 5.515MPa are extremely conservative. Based on this observation, the limit of 5.515MPa is not taken into account in the following calculations, while instead of $0.20f_c$, the less conservative, but still on the safe side, limit of $0.25f_c$ is used. It is noted, that also in this case, the partial safety factors for the materials are not taken into account.

CEB-fib Model Code 10 (2012), equation (Equ. (9)):

$$\tau_{ud} = 0.09 k_c f_{ck}^{1/3} + \mu (k \cdot \rho \cdot f_{yd} + \frac{\sigma_n}{\gamma}) + \alpha_F \sqrt{f_{yd} \cdot f_{cd}} \leq \beta_c \cdot f_{cd} \cdot b \text{ (N,mm)} \quad (9)$$

where: f_{ck}, f_{cd} denote the characteristic and the design concrete compressive strength

f_{yd} denotes the design yield strength of steel reinforcement crossing the interface

The interaction factors k and α_F in Equ.(9) take into account that the reinforcement or connectors are subject to bending and axial forces simultaneously and the maximum values of each mechanism occur at different slip values. The factor k_c is chosen according to the interface roughness. Finally the factor β_c is coefficient, used in order to reduce the compressive strength of a concrete strut.

The values of the abovementioned parameters are chosen according to Table.1.

Table 1. Factors for the calculation of the interface resistance, according to the interface roughness (CEB-fib Model Code 10, 2012).

Interface Roughness	c_k	k	α_F	β_c	M	
					f_{ck}≥20	f_{ck}≥35
Waterblasted interfaces, R≥2.5mm	2.3	0.5	0.9	0.5	0.8	1.1
Sandblasted interfaces, R≥0.5mm	0	0.5	1.0	0.4	0.7	
Smooth Interfaces	0	0	1.4	0.4	0.5	

As expected, the same basic parameters are taken into account in almost all equations found in the literature, namely: The percentage of the reinforcement crossing the interface, its yield strength, as well as the friction coefficient depending on the interface roughness. In some relationships, the concrete compressive strength is taken into account, in order to calculate the friction coefficient, or as an additional part of the equation, denoting the adhesion along the interface. It is noted that in most cases, (with the exception of Equ. (4), Tassios and Vassilopoulou, 2003) and Equ. (9), CEB-fib Model Code 10, 2012), only the contribution of the friction mechanism is taken into account, while the contribution of the dowel mechanism and its interaction with friction are ignored. It is noted, that in all investigated equations, no partial safety factors for concrete and steel are taken into account, given that the relationships are used in order to predict the resistance of tested interfaces.

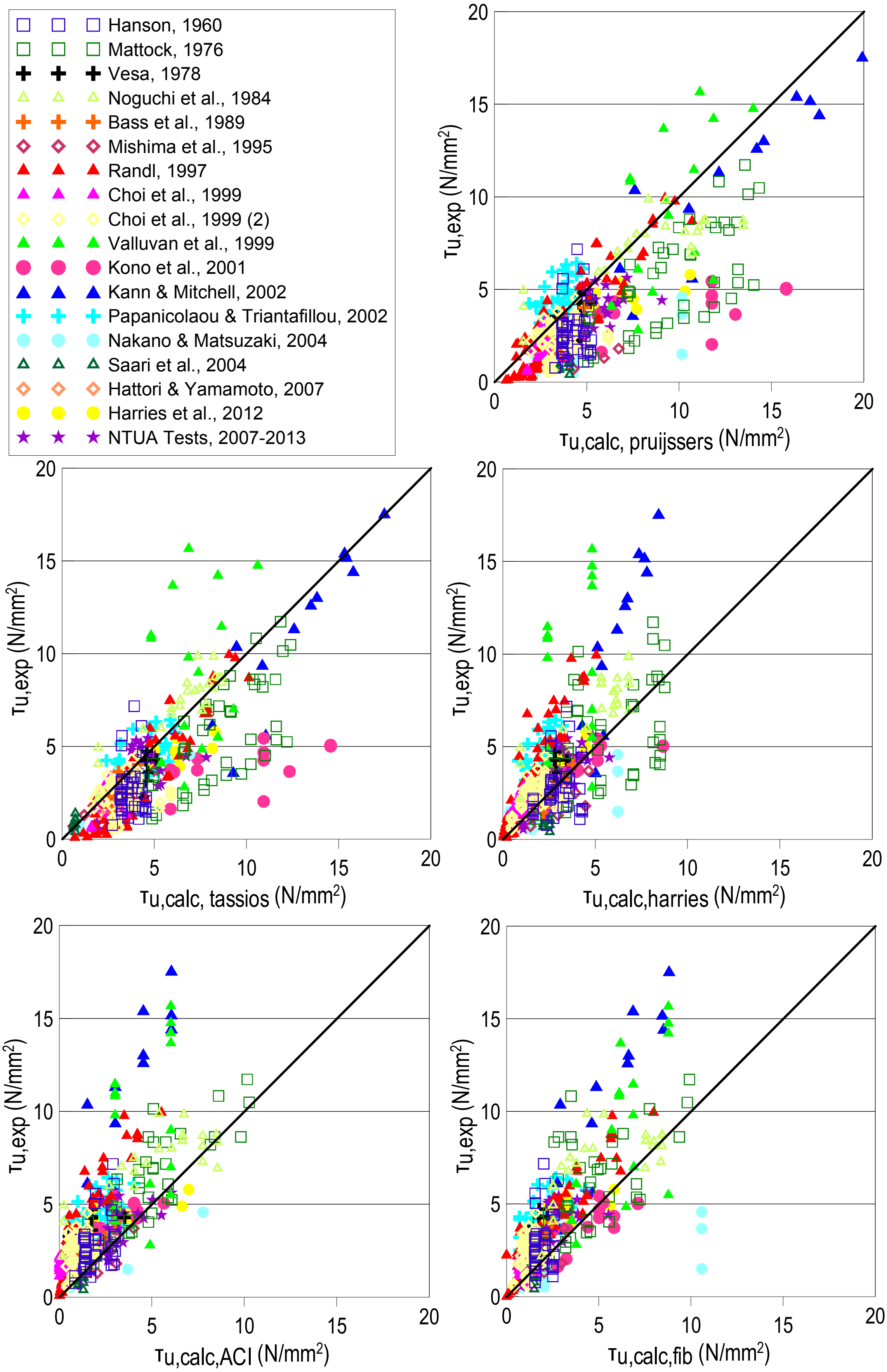


Figure 3. Comparison between the experimental results, and the resistance of the interface, calculated using various relationships of the Literature.

In Fig. 3, the values of the shear resistance of interfaces, calculated on the basis of the aforementioned equations are plotted against the respective experimental values. One may observe the significant scatter of the results of this comparison. Regarding each separate equation, one may comment as follows: The predictions according to Equ. (3) and to Equ. (4) (Pruijssers, 1988, Tassios and Vassilopoulou, 2003) are not on the safe side, as they yield systematically interface resistance values higher than the experimental ones. This is attributed to the fact that both equations were proposed for natural cracks and, hence, they do not yield accurate results in case of interfaces of limited roughness. On the contrary, Equ. (8), included in the ACI Code, applied as described previously (taking into account less conservative upper limits) leads to satisfactory results. Although Equ. (8) neglects the contribution of dowel action, the fictitiously higher friction coefficients proposed by the Code contribute to the calculation of realistic values for the overall shear resistance, Finally, Equ. (9) included in the CEB-fib Model Code 10 (2012), shows significant scatter. It should be noted that the values of shear resistance being calculated-for the needs of this comparison-without accounting for partial safety factors seem to be much on the unsafe side.

FORMULATION OF A MODIFIED RELATIONSHIP

Among the numerous relationships available in the Literature, that proposed by Tassios and Vassilopoulou (2003), is selected for further investigation. This choice is justified by the purpose of the present work: The design of interfaces in repaired or strengthened RC elements is carried out, according to current Codes (e.g. EC8, Part 3), for a given performance level. The shear slip expected to be imposed to the interface is a function of the design performance level. It is, therefore, necessary to provide the Designer with a formula able to take into account the contribution of each separate mechanism (a function of the imposed slip value), as well as the roughness of the interface, the presence of external normal stress, etc. The selected formula offers this possibility.

Thus, taking into account the available experimental data, the authors of this paper are proposing a set of modified factors to be implemented in Equ. (4):

Dowel action: The contribution of the mechanism to the overall resistance of the interface is taken equal to 70% the maximum resistance due to dowel action (i.e., β_d=0.70). For bars having an embedment length smaller or equal to 6 times the diameter of the bars (the length is compared to a length equal to 8 times the diameter of the bar, which is a length necessary for the full capacity of the dowel to be mobilized), the contribution of the dowel mechanism is reduced by a factor equal to 0.75. It is to be noted that the contribution of the dowel mechanism in the overall shear resistance of the interface is in general rather limited. It is expected to affect the overall resistance only for small imposed shear slip values, when the contribution of friction is also small.

Friction along the interface: The most significant modifications to the relationship proposed by Tassios and Vassilopoulou (2003) are brought to the part of the friction mechanism. The comparison between the experimental results and the values predicted by Equ. (4) show that the contribution of the friction mechanism cannot be accurately estimated, unless significant parameters, like roughness of the interface, presence of external normal stress, as well as type of loading (monotonic, cyclic or repeated) are taken into account.

First of all, Equ. (5) is modified: A coefficient equal to 0.33 is applied (instead of 0.44) to account for friction-dowel action interaction, as well as the fact that the interface is smoother than the one resulting from a natural crack. Thus, the contribution of friction is reduced by almost 25% and it is calculated according to the following Equ. (10):

$$\tau_f = 0.33\sqrt[3]{f_c^2 \sigma_c} \quad \text{(N, mm)} \tag{10}$$

Subsequently, on the basis of the re-evaluation of numerous experimental results, the following set of values are suggested for the contribution of the friction mechanism to the overall resistance of the interface (Table.2).

Table 2. Interfaces between old and new concrete: Contribution factors for the friction mechanism.

Interface Characteristics	β_f
Rough interface, monotonic loading	0.60
Smooth interface with external compressive stress	0.60
Smooth interface	0.40
Rough interface, cyclic loading, imposed shear slip s>1.00mm	0.40
Very smooth interface	0.20
Rough interface, cyclic loading, imposed shear slip s<0.20mm	0.20
Smooth interface, no cohesion along the interface	0.10
Rough interface with external compressive stress	0.80
Interface with shear keys	0.80

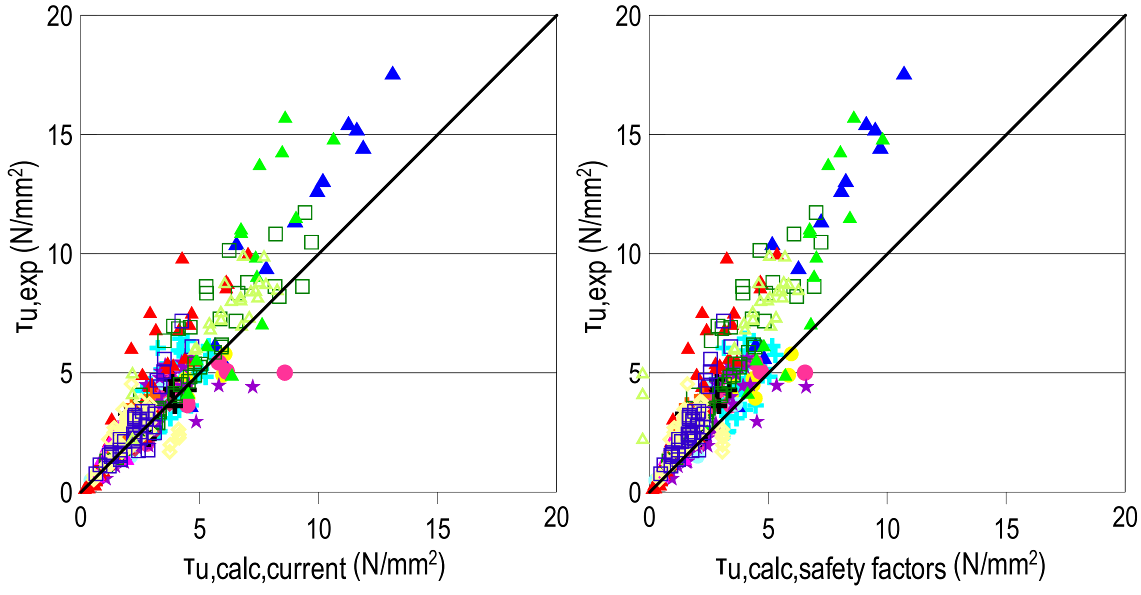


Figure 4. (a) Comparison between experimental shear resistance and values calculated on the basis of the proposed modified formula (b) Same as (a), taking into account partial safety factors for concrete and steel (1.50 and 1.15 respectively).

In Fig. 4 (a), the experimental values of the shear resistance are plotted against the values calculated according to the modified formula, whereas in Table 3, statistical data related to the efficiency of the formulae used for the calculation of the shear resistance of interfaces are provided. It seems that the experimental values are quite accurately predicted. The modified formula could be used for design purposes as well. As shown in Fig. 4(b), when in the modified formula, the design values of compressive strength of concrete and the yield strength of steel are introduced, the reduced predicted values of shear resistance of interfaces are adequate for the design of interfaces. Finally, the data included in Table 3 prove that the modified formula constitutes a clear improvement as compared with other formulae of the Literature.

Table 3. Statistical data related to the ratio between calculated and experimental value of the shear resistance of interfaces ($\tau_{u,calc}/\tau_{u,exp}$).

Equation	Pruijssers (1988)	Tassios and Vassilopoulou (2003)	Harries et al. (2012)	ACI Code (2011)	fib Model Code 10 (2012)	Modified formula
Average	1.78	1.64	0.90	0.60	0.78	0.91
Standard Deviation	1.23	1.22	0.62	0.36	0.51	0.28
Variation	1.51	1.48	0.38	0.13	0.26	0.08

CONCLUSIONS

The numerous experimental data of the literature regarding the shear resistance of RC interfaces are evaluated and used to check the efficiency of various relationships in predicting with acceptable accuracy the measured shear resistance values. Among the formulae used in this paper, the formula proposed by Tassios and Vassilopoulou (2003) was selected for further investigation, as it accounts for both shear transfer mechanisms, as well as for their interaction. A set of modified coefficients is proposed, based on a vast database (including almost 580 test results). The application of the modified formula has proved its satisfactory performance in predicting the shear resistance of interfaces subject to monotonic and cyclic shear displacements.

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