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Calculation of the interface resistance in RC construction using different codes

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ABSTRACT: The need for the assessment of interface shear strength in reinforced concrete construction arises in conjunction with a wide variety of structural details. Several design codes (e.g., EC2, ACI 318, MC 2010) provide guidance on the design of interfaces, assuming full anchorage of the interface dowels. As dowels, cast-in reinforcing bars, are typically assumed. Nevertheless, in case of repair and strengthening of structures, the interface dowels are usually post-installed in the existing concrete member, while their embedment length may be limited. The European Organization for Technical Assessment has issued a design Guideline (EOTA TR 066 2019), allowing to design interfaces with connectors of limited anchorage. To cover the cyclic behavior of interfaces, an extension of the guidelines, amended in 2020, was introduced. In the current paper, the equations for the prediction of interface resistance, included in the codes and guidelines are compared with experimental results, are evaluated, and commented upon.

1 INTRODUCTION

Interfaces being loaded in shear, occur along crack surfaces that develop at points of maximum shear, in cold joints resulting from construction sequencing and between precast elements. The calculation of the interface resistance is particularly relevant for repair and strengthening of structures, where, because of geometrical limitations of existing elements and added overlays, the embedment of the interface reinforcement may be limited. For example, the thickness of an existing slab is limited, in most cases not exceeding 10-12cm, while also the thickness of the added overlay is limited, in order to avoid the excessive increase of the self-weight of the structure.

Several design codes (e.g., EC2 2004, ACI 318 2019, MC 2010 and various National Codes) provide guidance on the design of interfaces. The codes provide equations for the calculation of shear resistance, for interfaces that are smooth, rough or very rough. No guidance is offered regarding the way in which the interface roughness should be measured, except than in MC 2010, which proposes the sand patch method (Kaufmann 1971). It is though noted that this method cannot be used in case of non-horizontal interfaces. Additionally, these design provisions typically assume full anchorage of the dowels crossing the interface, i.e., their anchorage length is sufficient to allow the interface reinforcement to develop its yield strength. As dowels, cast-in reinforcing bars, perpendicular or inclined to the interface, are typically assumed. Nevertheless, strengthening measures in most cases require installation of the dowels in the existing reinforced concrete member, thus making a cast-in solution unfeasible. Last but not least, the codes do not cover the case of cyclic loading of the interfaces. Experimental investigations (Bass et al. 1989, Valluvan et al. 1999, Cattaneo et al. 2021, Palieraki et al. 2023) have shown that the interface resistance is reduced due to cyclic loading, while the amount of the reduction depends on various parameters, such as the concrete strength, the roughness of the interface, the type of the interface reinforcement, the embedment depth and the amplitude of the applied shear slip.

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The European Organization for Technical Assessment has issued a design Guideline (EOTA TR 066 2019), which allows to design interfaces with shear connectors provided with an anchorage length smaller than the one required for full anchorage and considering the properties of engineered connectors in terms of material ductility, cross section geometry and pullout resistance. In order to cover the cyclic behavior of interfaces crossed by different types of connectors, an extension of the EOTA guidelines was recently introduced (EOTA TR 066 2019, amended 2020).

In the current paper, the equations for the prediction of the interface resistance, included in codes, and technical documents are compared with experimental results, they are evaluated and commented upon.

2 CODE PROVISIONS

The equations included in some of the current design codes, are presented in Table 1. In those equations the interface resistance is expressed in terms of interface shear stress (MPa).

Table 1. Design codes equations for the calculation of interface resistance.

Code	Equation
EC2 (2004)	$\tau_{calc}= \mathrm{c}\cdot f_{\mathrm{ctd}}+\mu\cdot\sigma_{\mathrm{n}}+\rho\cdot f_{\mathrm{yd}}\cdot(\mu\cdot\sin\alpha+\cos\alpha)\leq 0.5\cdot \mathrm{v}\cdot f_{\mathrm{cd}}$
ACI 318 (2019)*	$\tau_{calx} = \rho\cdot f_{\mathrm{y}}\cdot(\mu\cdot\sin\alpha+\cos\alpha)$
MC 2010 (2010)	$\tau_{calc} = c_{\mathrm{r}}\cdot f_{\mathrm{ck}}{}^{1/3}+\mu\cdot\sigma_{\mathrm{n}}+\kappa_1\cdot\rho\cdot f_{\mathrm{yd}}\cdot(\mu\cdot\sin\alpha+\cos\alpha)+\kappa_2\cdot\rho\cdot(f_{\mathrm{yd}}\cdot f_{\mathrm{cd}})^{1/2}\leq\beta_{\mathrm{c}}\cdot \mathrm{v}\cdot f_{\mathrm{cd}}$

*Upper limits are proposed for the ACI 318 equation, depending on the roughness of the interface

where,

τ_{calc} = interface resistance, calculated using the equations proposed in the codes or guidelines

f_{ctd} = design tensile strength of concrete

$f_{\mathrm{ck}}, f_{\mathrm{cd}}$ = characteristic and design compressive strength of concrete, correspondingly

$f_{\mathrm{y}}, f_{\mathrm{yd}}$ = nominal and design yield strength of steel, crossing the interface, correspondingly

α = angle of the reinforcement with the perpendicular to the interface

σ_{n} = stress caused by the minimum external normal force across the interface (positive for compression)

ρ = percentage of the interface reinforcement

v, β_{c} = coefficients related to the concrete strength, described in EC2 (2004), MC2010 (2010)

c, c_{r}, μ, κ_1, κ_2 = factors which depend on the roughness of the interface

In the equations of Table 1, there are common terms, corresponding to the mechanism of shear friction, namely, the friction coefficient, μ, the percentage of the interface reinforcement, ρ, and the yield strength of steel, f_{yd}. The remaining terms are met in one or more equations and they refer to the adhesion along the interface and/or to the dowel action of the interface reinforcement. It is noted that in almost all equations, an upper limit is set for the interface resistance, equal to a percentage of the compressive strength of concrete. In ACI 318 (2019), this upper limit depends on the roughness of the interface, while there is an additional upper limit, a fixed value of the interface resistance, which depends again on the interface roughness.

The provisions of equations included in the codes and the guidelines, were compared to the experimental results included in a database (Palieraki et al. 2021). The data were obtained from testing interfaces within monolithic specimens, as well as cold joints, i.e., interfaces between concretes cast at different times. In the current paper, the data on cold joints, in total 868 test results, are analyzed.

The database covers a wide range of parameters. The compressive strength of the weaker concrete varies between 6MPa and 120MPa, while the most common values are between 12MPa and 60MPa. The yield strength of the reinforcement ranges between 300MPa and 700MPa, with the higher value being exceeded in a very small number of tests. The reinforcing bars are anchored in the concrete by means of bond, or by means of adhesive material. In a limited number of tests, special reinforcement is used (screws or bolts). The reinforcement may be in the form of closed hoops, thus, allowing for the assumption of full anchorage to be made, it may be straight and fully anchored, or it may be of limited length, which does not allow yielding of the reinforcement. In most of cases, rough or very rough interfaces are tested, while the specimens with smooth or very smooth interface, as defined in the fib Model Code (MC 2010), do not exceed the 15% of the total number of specimens.

As already mentioned, the design provisions included in the codes, typically assume full anchorage of the reinforcement crossing the interface. Nonetheless, in the fib Model Code (MC 2010), it is stated that the tensile force to be anchored may be assumed equal to a percentage, κ, of the force required for the tensile stress to be fully developed (Paragraph 6.3.5, Equ. 6.3-8).

For the assessment of the various equations, the database is divided into two parts: (a) Tests in which the reinforcement is anchored to a length that allows the development of its yield strength (605 tests). This category includes specimens reinforced with closed hoops, cast-in reinforcing bars with a bonded length larger than $20d_b$ in either side of the interface, and post-installed reinforcement, with a bonded length (in epoxy material) greater than $10d_b$, and (b) Tests on interfaces (189 specimens), where the reinforcement does not fall into one of the cases of category (a).

The plots of Figure 1 prove that even in case of interfaces reinforced with fully anchored bars, the predictions of the equations included in Table 1 are not always conservative. It is noted that the equations were applied without any safety factor on the properties of the materials. Nonetheless, even when safety factors relevant to each code are used (Figure 2), there is still a small percentage of cases, for which the equations remain unconservative. The most significant statistical values resulting from the application of the code equations are reported in Table 2.

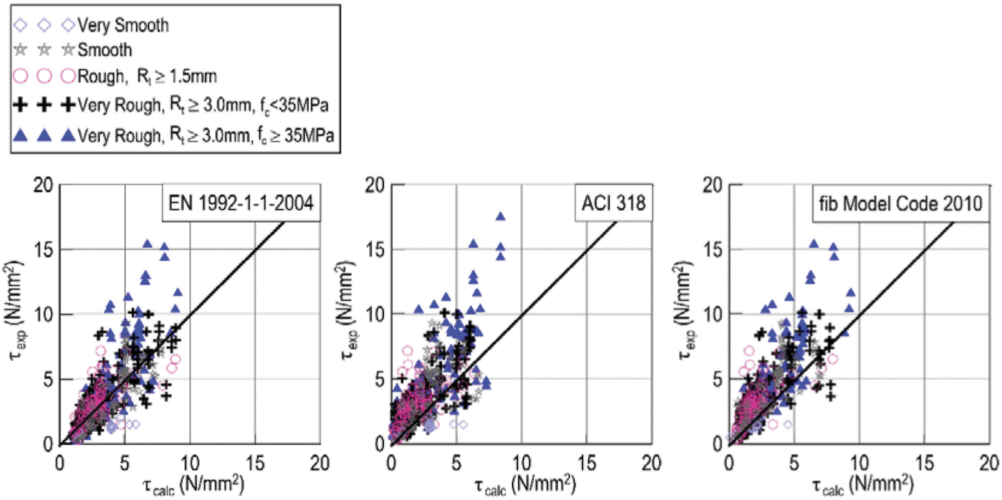
In case of interfaces crossed by short reinforcement, which cannot reach yielding, the comparison between experimental and predicted interface resistances is expected to yield unconservative results in a significant number of cases. This is confirmed by Figure 3, where in the calculated interface resistances safety factors are accounted for.

The codes that are assessed in this work are not meant for use in seismic design. Nonetheless, they are evaluated for this case as well, because ACI 318 (2019) is used in practice for seismic design of interfaces as well, while EC8 (2005) (its Part 3 included) refers to the EC2 (2004) equation for the design of interfaces. Finally, in the fib Model Code (MC 2010), there is a provision exclusively for unreinforced interfaces, penalized with a reduction factor of 0.50. In Figure 4, the code provisions are plotted against experimental values obtained from cyclic tests on interfaces. It is noted that in those plots, the reduction due to cycling interface resistance is accounted for. Both the plots of Figure 4 and the statistical data of Table 2 prove that the current code provisions cannot cover in a conservative way the design of interfaces subjected to seismic actions.

3 CHANGES TO THE TR 066 FOR CYCLIC LOADING

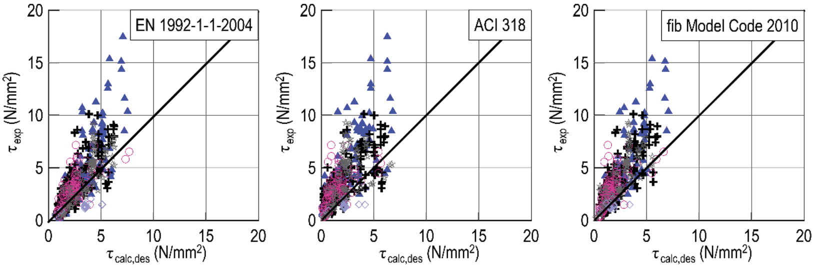
As analyzed in the previous section, the evaluated code provisions are not adequate, especially for interfaces with reinforcement of limited anchorage, as well as for the design of interfaces subjected to cyclic loading. Thus, in the framework of EOTA, the equation of the fib Model Code (MC 2010) was modified as per TR 066 (2019) (Table 3). The main difference between the two equations, lies in their third term: The compressive stress, σ_c, used for the calculation of the friction coefficient, μ, i.e. the stress due to clamping effect, is calculated as $\sigma_c=\rho\sigma_s$, σ_s being the tensile stress of the reinforcement crossing the interface and calculated using the following equation: $\sigma_s = l_{emb}*f_{yd}/l_b$, where $l_b=f_{yd}*d_b/(4*f_{bd})$.

Therefore, the tensile stress of the reinforcement is not assumed to be equal to the yield strength of steel, but it is calculated on the basis of the available anchorage length of the interface reinforcement, and it is associated to the relevant failure mode. In case of post-installed reinforcing bars or industrial connectors, the value of τ_{Rd} (bond strength) provided by the respective manufacturer (based on evaluation tests) is used in the abovementioned Equation in lieu of f_{bd}. When interfaces are crossed by short post-installed bars (embedment length between $6d_b$ and $10d_b$), to predict their reduced bearing capacity, the verification for concrete cone breakout capacity is also required. The results of the application are presented in



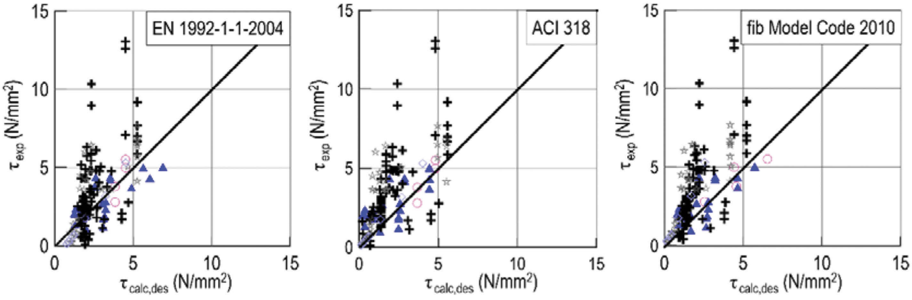
(a) (b) (c)

Figure 1. Specimens crossed by sufficiently anchored reinforcement: Comparison between experimental interface resistances and (a) Eurocode 2 (EN 1992-1-1-2004), (b) ACI 318 (2019) code, (c) fib Model Code (MC 2010). No safety factors are used.



(a) (b) (c)

Figure 2. As Figure 1, with the use of relevant safety factors, namely, 1.15 and 1.50 for steel and concrete, respectively, for (a) and (c), and global safety factor φ=0.75 in (b).



(a) (b) (c)

Figure 3. Specimens crossed by reinforcement with limited anchorage length: Comparison between experimental interface resistances and (a) Eurocode 2 (EN 1992-1-1-2004), (b) ACI 318 (2019), (c) fib Model Code (MC 2010). For the calculations relevant safety factors are used.

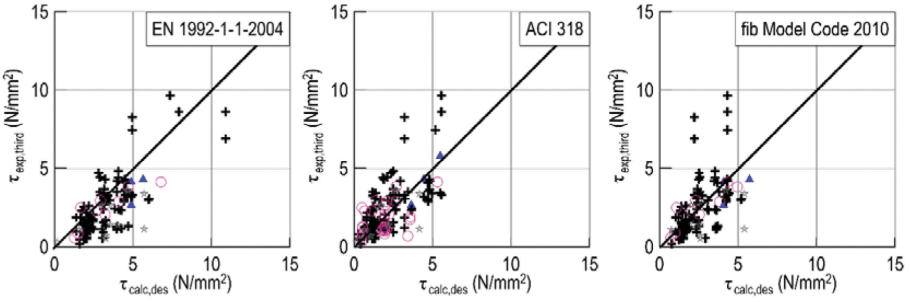
Table 2. Comparison between experimental interface resistances and code provisions. Statistical data.

Reinforcement	Bars that may yield			Bars of limited length			Cyclic loading		
	τ_c/τ_{exp}	$\tau_{c,des}/\tau_{exp}$	$\tau_{c,des}/\tau_{exp} > 1.0$	τ_c/τ_{exp}	$\tau_{c,des}/\tau_{exp}$	$\tau_{c,des}/\tau_{exp} > 1.0$	τ_c/τ_{exp}	$\tau_{c,des}/\tau_{exp}$	$\tau_{c,des}/\tau_{exp} > 1.0$
Code	Average Values		Uncons. Values	Average Values		Uncons. Values	Average Values		Uncons. Values
EC2 (2004)	1.161	0.954	193	1.578	1.254	52	2.299	1.852	106
CoV (%)	55.3	55.5		142.2	141.8		70.8	67.7	
ACI 318 (2019)	0.777	0.598	66	0.850	0.677	17	1.456	1.121	65
CoV (%)	57.5	58.6		88.7	85.7		57.8	60.6	
MC 2010 (2010)	0.771	0.670	76	0.795	0.672	19	1.522	1.442	65
CoV (%)	43.8	43.7		55.3	57.1		73.6	66.0	
TR 066 (2020)				0.689	0.586	11	0.889	0.606	13
CoV (%)				52.3	56.0		44.1	48.2	

Uncos. Values stands for Unconservative Values

τ_c (τ_{calc}) is the value of the interface resistance calculated without the use of relevant safety factors

$\tau_{c,des}$ is the value of the interface resistance calculated with the use of relevant safety factors



(a) (b) (c)

Figure 4. Interfaces subjected to cyclic actions. Comparison between experimental interface resistance measured during the third cycle, and values calculated according to (a) Eurocode 2 (EN 1992-1-1-2004), (b) ACI 318 (2019), (c) fib Model Code (MC 2010). For the calculations, relevant safety factors are used.

Figure 5 a, b. It is noted that the information regarding the exact values of f_{bd} or τ_{Rd} are not available for the reinforcement of all tested specimens, therefore the value of σ_s is calculated as: $\sigma_s = l_{emb}*f_{yd}/20d_b$, in case of cast-in reinforcement and $\sigma_s = l_{emb}*f_{yd}/10d_b$, in case of post-installed reinforcement. The prediction is more conservative, and a limited number of data points is unconservative.

Table 3. The equations included in TR 066 (2019), and version amended in 2020.

Technical Report	Equation
TR 066, 2019	$\tau_{calc} = c_r \cdot f_{ck}^{1/3} + \mu \cdot \sigma_n + \mu \cdot \kappa_1 \cdot \alpha_{\kappa 1} \cdot \rho \cdot \sigma_s + \kappa_2 \cdot \alpha_{\kappa 2} \cdot \rho \cdot (f_{yd} \cdot f_{cd})^{1/2} \leq \beta_c \cdot v \cdot f_{cd}$
TR 066, amended 2020	$\tau_{calc} = \alpha_{seis} \cdot [c_r \cdot f_{ck}^{1/3} + \mu \cdot \sigma_n + \mu \cdot \kappa_1 \cdot \alpha_{\kappa 1} \cdot \rho \cdot \sigma_s + \kappa_2 \cdot \alpha_{\kappa 2} \cdot \rho \cdot (f_{yd} \cdot f_{cd})^{1/2}] \leq \beta_c \cdot v \cdot f_{cd}$

In the equations of Table 3, c_r, κ_1, $\alpha_{\kappa 1}$, κ_2, $\alpha_{\kappa 2}$ and αs_{eis}, are factors depending on the roughness of the interface, on the type of the product used as interface reinforcement, as well as on the type of loading, namely monotonic or cyclic.

The equation of TR 066 (2019) does not account for reduced interface resistance due to cyclic loading. This was made possible by the additional provisions of the amended version of TR 066 (2020). It is noted that the method described in the Technical Report TR 066, both versions, deals with the design of connections realized using products covered by an ETA based on EAD 332347-00-0601 (2019) or EAD 332347-00-0601-v01 (2020).

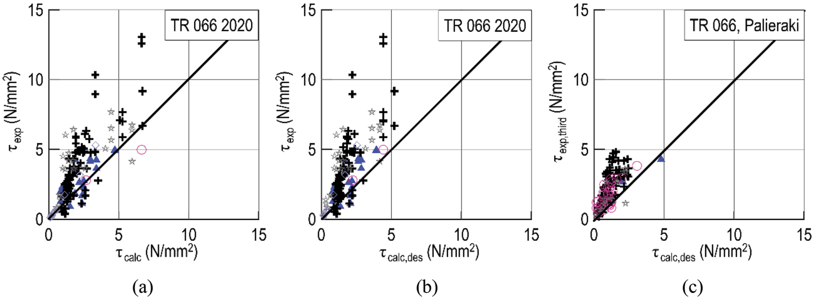


Figure 5. Specimens crossed by reinforcement with limited anchorage length: Comparison between experimental interface resistances and TR 066, for monotonic loading. For the calculations relevant safety factors (a) are not used, (b) are used, (c) Prediction for cyclic loading, using TR 066, in combination with α_{seis}, as proposed in Palieraki et al., 2022.

The equations included in the two versions of the Technical Report TR 066, are similar, in the sense that they account for both mechanisms of shear transfer along reinforced interfaces, namely, friction (due to external normal stress and due to clamping effect of the connectors) and dowel action. Both equations set the same limiting value for the resistance of the interface (the failure of concrete strut). It is noted that the equation in the amended version, is based upon the model presented in Palieraki et al. (2022). The main modifications of the amended version of TR 066 (2020), applicable to interfaces subjected to seismic actions, are the following:

(a) Interfaces characterized as "very smooth" are excluded, given that their resistance is very small even under monotonic loading, and, thus, they are inadequate for use under seismic conditions.
(b) The term of adhesive bond resistance/aggregate interlock, added to the resistance due to friction and to dowel action in the current equation is neglected in the new version of the equation. Indeed, in case of seismic actions, under the application of cyclic shear slips at values that exceed those (extremely small) needed for the mobilization of the adhesive bond resistance/aggregate interlock, this mechanism is not any more active. Additionally, another major change is needed, as explained herein:
(c) In the equation included in the TR 066 (2019), for static loading, conservative (safe for the design) friction coefficient values are adopted. Those values depend exclusively on the roughness of the interface. Although it is well known that the friction coefficient is not constant, as it depends on the normal stress acting on the interface, it is understood that the need for a simple and safe calculation of the shear resistance of interfaces led to the adoption of friction coefficients independent of the value of the normal stress.
On the contrary, and due to the fact that the embedment length of the post-installed anchors is, in most cases, smaller than the one required for full development of the yield strength of the steel, the normal (compressive) stress on the interface is expected to be in several cases rather limited in value. For this frequent case, constant friction coefficient values (depending on the roughness of the interface), in combination with the reduction factors that account for the cyclic behavior, would lead to overconservative (unrealistically small) design values for the resistance of interfaces. Thus, on the basis of the available experimental data (taken from the international literature), a simple equation is proposed for the calculation of the friction coefficient, depending on the normal stress acting on the interface normalized to the compressive strength of the concrete. The friction coefficient is calculated using the following equation:

$$\mu = c \cdot \sqrt[3]{\left(\frac{f_{cd}}{\sigma_c + \sigma_n}\right)^2} \tag{1}$$

where the factor c, depends on the roughness and the concrete strength.

(d) Last but not least, when the interface is under the adverse condition of cyclic actions, there are four phenomena that lead to the reduction of the maximum shear resistance (taken into account through the coefficient $\alpha_{seis} = \alpha_{seis,1} * \alpha_{seis,2} * \alpha_{seis,3} * \beta_{seis}$, Figure 6), namely: (i) the maximum shear resistance under cyclic actions is smaller than the one corresponding to monotonic action ($\alpha_{seis,1}$), (ii) there is an asymmetry of behavior in the two loading directions, and in most cases, the load along the second loading direction is smaller ($\alpha_{seis,2}$), (iii) the shear resistance is decreased due to cycling ($\alpha_{seis,3}$), while (iv) larger scatter is associated with the seismic behavior of interfaces (β_{seis}). Thus, compared to the static resistance of an interface, its cyclic resistance is decreased by a significant percentage (depending, of course, on the specific anchor, on the roughness of interface, etc.).

For the equation included in the amended version of the TR 066, the coefficient α_{seis} should be calculated, according to tests, as described in the EAD 332347-00-0601-v01 (2020). Nevertheless, such tests are not available for the results reported in the literature, the calculations are performed based on Palieraki et al. (2022), using a reduction factor equal to 50%. The results are presented in Figure 5c and Table 2. The equation is quite conservative, while also the coefficient of variation is high, but this is expected to be corrected, when the values of α_{seis} calculated according to the test results are used.

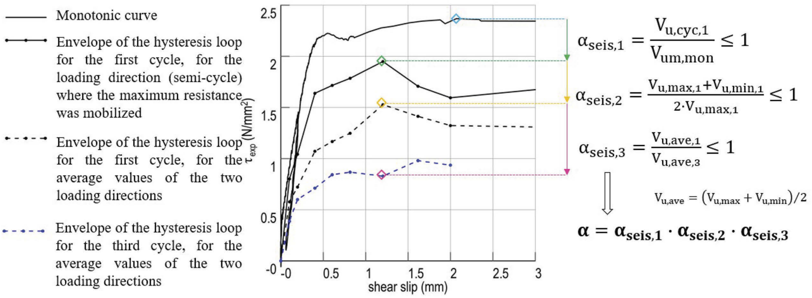


Figure 6. Typical curves reported for monotonic and cyclic loading, for the first, second and third cycle. The reduction factors due to cyclic loading, $\alpha_{seis,1}$, $\alpha_{seis,2}$, $\alpha_{seis,3}$ are shown in the relative curves.

4 CONCLUSIONS

The current paper provides a comparison of interface shear experimental results on cold joints, with shear resistance values calculated according to the EC2 (2004), ACI 318 (2019) and fib Model Code (MC 2010) provisions, as well as to the two versions of the design Guideline (EOTA TR 066 2019 and amended version, 2020).

The comparison shows that the calculations according to the equations of the assessed current codes, are in most cases conservative, leading at the same time to the overestimation of the results of part of the tests. This conclusion is valid for interfaces provided with reinforcement anchored to allow yielding. In case of interfaces provided with reinforcement of limited embedment length, or interfaces subjected to cyclic loading, the calculated resistance values are in average larger than the experimental resistances. Furthermore, in all cases, the scatter of the ratio between predicted and calculated values of interface resistances, expressed by the coefficient of variation, is very high.

An alternative equation is proposed as an improvement over the current interface shear provisions of fib Model Code (MC 2010) and is included in the Technical Report TR 066 (2019), for the calculation of the shear resistance of interfaces reinforced with post-installed reinforcement of limited length. This formulation accounts for the shear friction and the dowel action, while the tensile stress of the reinforcement, which is taken into account for the calculation of the friction term, is considered reduced, corresponding to the available embedment length. The alternative equation is more conservative and leads to a reduced number of points on the unconservative side.

In addition to the inaccuracy of the code equations in case of bars of limited length, the reduced shear resistance due to cyclic loading in not accounted for. Nonetheless, the provisions used in practice for seismic conditions as well, lead to unconservative results. The amended in 2020 version of the TR 066, provides a modified equation for the calculation of this reduced resistance. The application of the modified equation has proven its satisfactory performance in predicting the shear resistance of cold joint interfaces, subjected to cyclic loading.

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