CESARE'14 International Conference Civil Engineering for Sustainability and Resilience
Amman, 24-27.04.2013

SHEAR RESISTANCE OF INTERFACES BETWEEN EXISTING AND NEW RC ELEMENTS

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Keywords: Interface, Shear resistance, Aggregate interlock, Dowel, Design, Relative slip.

Abstract. *Estimation of the shear resistance of interfaces between old and new concrete is essential in the design of strengthening of existing RC structures, especially when the interfaces are designed against seismic actions. The interface should not fail when subjected to the maximum expected forces. Shear resistance of an interface depends on various parameters, more important of which are the preparation of the interfaces and the quality of execution of works. The magnitude of relative slip of the two sides of the interface is essential for the assessment of the resistance of an interface, but it is difficult to predict at the phase of design.*

In this work three representative design models for estimation of the shear interface transfer are briefly reviewed and are applied to predict the experimental resistance of specimens tested in the literature. The adequacy of the models is discussed in relation to their predictive power and the different assumptions of the models. Code provisions of MC2010, ACI318-11 and Eurocode 2 for the design of interfaces are discussed and applied to predict the shear resistance of the test specimens. The behavior of the interface of RC infilled frames tested in the University of Thessaly is also simulated and discussed.

1 INTRODUCTION

One of the major problems in strengthening of existing reinforced concrete (RC) buildings is the estimation of the behavior of the interfaces between old and new concrete. In design and detailing of strengthened and/or repaired RC structural elements assumptions have to be made regarding the stiffness and the strength of the composite new element, not only for the cross-sections but also for the behavior of the whole element.

This work, part of which is presented here, was an attempt for the interpretation of the test results of a project carried out in the Laboratory of Concrete Technology and RC Structures in the University of Thessaly Reinforced Concrete Structures of the University of Thessaly, Greece. One third (1/3)-scale tests were carried out on RC frames reinforced by RC infill walls constructed at least 28 days after the casting of the RC frames. Different ways of connection of the infills to the frame were tested: with or without roughening of the concrete interface, with or without reinforcing steel bars (chemical dowels) intersecting the interfaces. The infilled walls were subjected to quasi static cyclic horizontal shear force at the mid-height of the beam. More details about the tests may be found elsewhere [1], [2]. The main conclusion from the tests confirmed previous similar experimental investigations, and may be summed up as follows: The stronger the connection of the RC infill wall to the frame, the better the overall behavior of the infilled frame. The occurrence of significant relative slip in the interface between the frame and the infill led generally to deterioration of the overall behavior both in terms of strength and ductility.

The objective of this work was the estimation of the behavior of the horizontal interfaces between the infill and the frame beam or the foundation block, at the top and at the bottom of the infill, respectively. It is noted that in the tests failure occurred usually along one of these two horizontal interfaces of the infill. In case reinforcement bars were present along the infill/frame horizontal interfaces they were sheared off in their majority. In order to assess the overall shear resistance of the infill/frame horizontal interfaces initially a review of the interface shear transfer mechanisms was carried out. Certain design expressions offered in the literature were evaluated by being applied to estimate the shear strength of specimens tested, the predictions being compared to the actual measured shear strengths. Further on, code provisions for the shear strength at interfaces were also applied to test results from the literature. The best description of the behavior of the infill/frame interfaces of specimens with roughened interfaces was achieved by the application of the more sophisticated model proposed by Walraven [3].

In what follows some results of the application of certain models and design codes for the strength prediction of shear tests available in the literature are presented and discussed. Also the estimation of the shear-slip behavior of a horizontal infill/frame interface of an RC infilled frame tested will be presented and compared to the experimental one.

2 SHEAR STRENGTH AT INTERFACES BETWEEN OLD AND NEW CONCRETE

2.1 General

Research on interface shear transfer dates back to the 1960's for precast concrete connections [4]. The mechanisms of load transfer activated along interfaces are adhesive bond (cohesion), aggregate interlock, friction and dowel action. Relative slip between the sides of the interface triggers the activation of these load bearing mechanisms. Maximum activation of each mechanism is achieved at different values of shear slip, s. As it has been established from tests, adhesion is lost for values of slip s > 0.05 mm. In presence of reinforcing bars at the interface, maximum shear resistance is achieved for rough interfaces at s =0.5 – 1.5 mm, while for smooth interfaces for higher values of slip [5].

The contribution of the load carrying mechanisms depends strongly on the interaction between the mechanisms, especially in the presence of reinforcement at the interface. The contribution of reinforcement bars that intersect the interface which is one of the major parameters in the shear strength of the interface is obtained in a two-fold manner: a) The bars carry immediately shear force through dowel action, and b) The tension developed in the reinforcement bars that cross a joint provide an external clamping force on the two parts of the joint, resulting in compression of equal magnitude which, in turn, enhances the activation of friction due to aggregate interlock (first expressed as “shear friction theory” [4]). The majority of the available design expressions include this assumption.

The amount of roughening of the interface is the other essential parameter in shear transfer and the way this parameter is taken into account differs significantly in the various analytical expressions available. A state-of-the-art overview of the most important design expressions [6] is most informative regarding the evolution in this field. In this work the application on test results of three design equations as well as three code provisions, which were judged as most representative, will be presented.

2.2 Predictions of three analytical models on test specimens

The design expressions that will be used to compare the analytical predictions to test results are briefly presented in the following:

First the expression proposed in 1974 by Mattock [7], based on a previous expression [8], which was the first to take into account the adhesion by a constant parameter, shown in eqn (1).

$$v_u = 2.76 + 0.8(\rho f_y + \sigma_n) \text{ (MPa)} \tag{1}$$

where v_u is the shear strength of the interface, σ_n is the normal stress at the interface, ρ is the reinforcement ratio and f_y is the yield stress of the steel bars that intersect the interface. The shear strength is limited by both 0.3 f_c and 10.34 MPa. Also $\rho f_y > 1.38 MPa$ should apply.

The second design equation used herein was proposed by Mansur et al. [9] and was based on previous research. It proposes three different expressions depending on the value of the normalized clamping force $\rho f_y / f_c$, as displayed in eqn (2), all strengths being introduced in MPa:

$$\begin{aligned} \frac{v_u}{f_c} &= 2.5\frac{\rho f_y}{f_c} && \text{for} \quad \frac{\rho f_y}{f_c} \le 0.075 \\ \frac{v_u}{f_c} &= \frac{0.56}{f_c^{0.385}} + 0.55\frac{\rho f_y}{f_c} && \text{for} \quad 0.075 < \frac{\rho f_y}{f_c} \le 0.270 \\ \frac{v_u}{f_c} &= 0.3 && \text{for} \quad \frac{\rho f_y}{f_c} > 0.270 \end{aligned} \tag{2}$$

Finally the expression proposed by Randl [10] was also used. This expression has been adopted by the Model Code 2010 [11]. It includes independently the contribution of the three load carrying mechanisms, i.e. cohesion and aggregate interlock, friction and dowel action. Different values of the constant parameters involved in each mechanism are proposed depending on the roughness of the interfaces. This design expression (equ. 3), although it is in cases very conservative, is proved to offer the most safe predictions among the expressions examined in this work.

$$v_{Rd} = c_r \cdot f_{ck}^{1/3} + \mu \cdot \left(\sigma_n + \rho \cdot \kappa_1 \cdot f_{yd}\right) + \kappa_2 \cdot \rho \cdot \sqrt{f_{yd} \cdot f_{cd}} \leq \beta_c \cdot \nu \cdot f_{cd} \tag{3}$$

where $c_r, \mu, \kappa_1, \kappa_2, \beta_c$ are coefficients that depend on the surface roughness and may be found in detail in references [10] or [11]. It is noted that the design strengths of concrete and steel, f_{cd} and f_{yd}, respectively are included in eqn (3). They are derived by applying the partial safety factors $\gamma_c = 1.5$ for concrete and $\gamma_s = 1.15$ for steel to the respective characteristic strengths of materials. The upper limit of the interface shear capacity (crushing of diagonal concrete strut) depends also on the characteristic strength of concrete and is depends on the factor $\nu = 0.55 \cdot \left(30 / f_{ck}\right)^{1/3} \leq 0.55$, f_{ck} in MPa

Test results on different kinds of interfaces, i.e. rough, smooth and monolithic specimens, were used to evaluate the three expressions [12], [13], [14], 64 specimens in total. The actual material strengths were used in the calculations and not the reduced (design) ones.

In Figure 1 the l predictions calculated from eqs (1), (2) and (3) are plotted against the product of the ratio of the reinforcement across the interface, ρ, multiplied by the respective yield stress, f_{sy}, which expresses the clamping force across the interface. The three equations all express the observed increase in shear strength with the increase of the amount of reinforcement at the interface. The predictions of Randl [10] are clearly the most conservative.

In Figure 2 are compared the measured shear strengths with the analytical predictions from eqs (1) to (3). It is evident that the expressions of Mattock [7] and Mansur et al. [9] overestimate the interface shear strength in case of smooth interfaces, while their predictions for rough interfaces are very good. The shear strength calculated according to Randl [10] are all safe, while the predictions for rough interfaces seem to be particularly conservative.

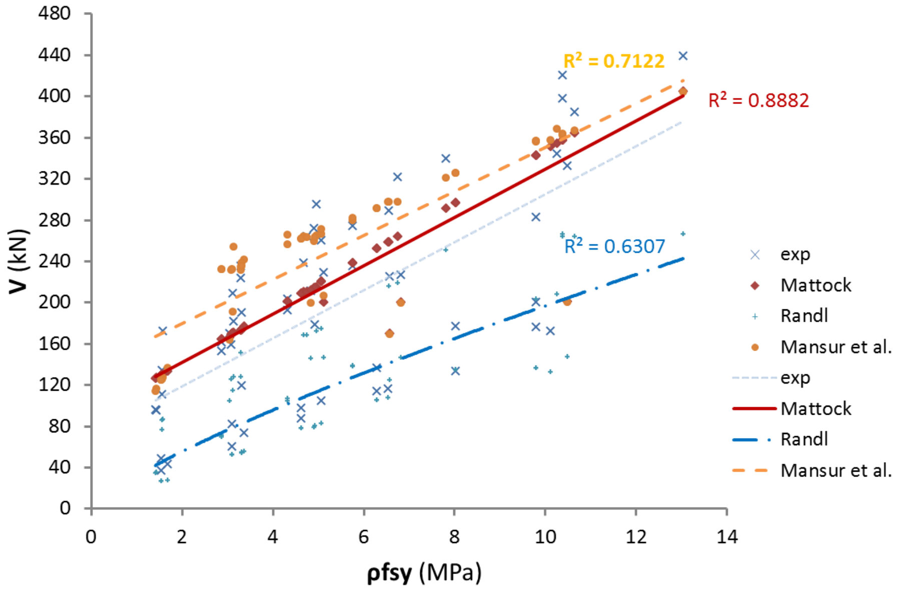


Figure 1. Shear strength vs. amount of reinforcement across interface [20].

2.3 Design Codes

The design equation of Eurocode 2 (EN1992-1-1) [15] is shown in eqn (4):

$$v_{Rd} = c \cdot f_{ctd} + \mu \cdot \sigma_n + \rho \cdot f_{yd} \left(\mu \sin a + \cos \alpha\right) \leq 0.5 \cdot \nu \cdot f_{cd} \tag{4}$$

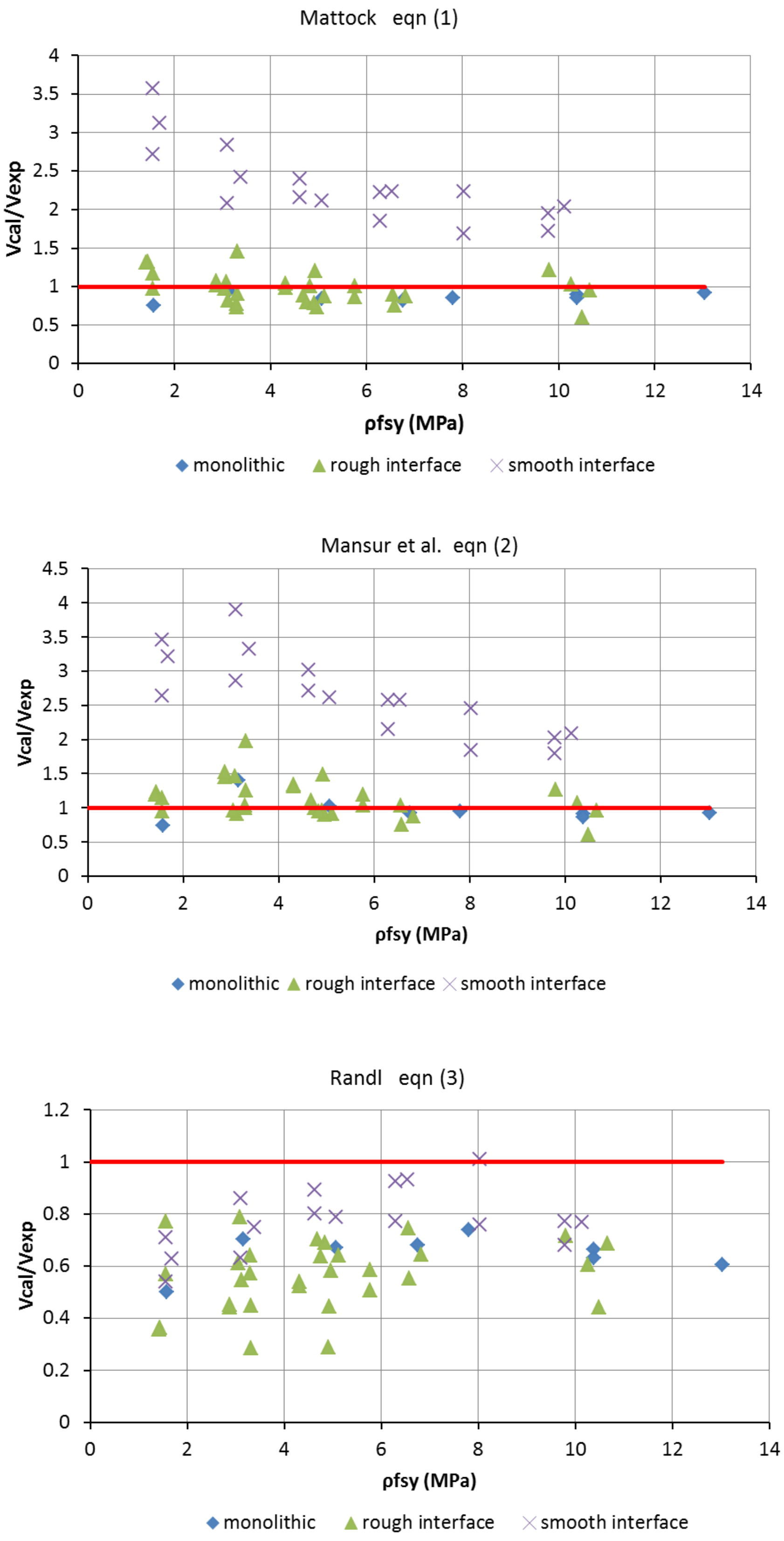
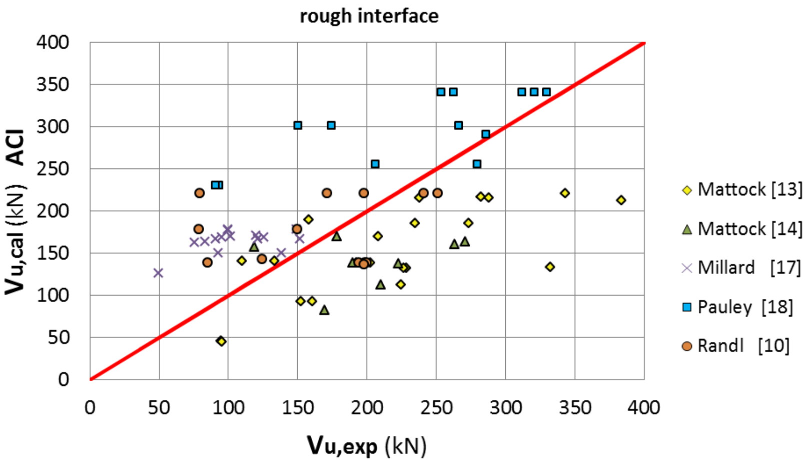
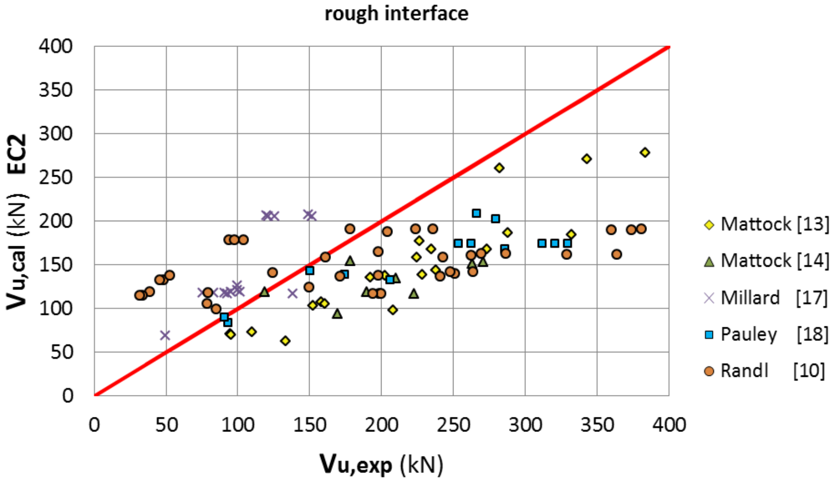


Figure 2. Ratio of analytical to experimental shear strength vs. reinforcement across interface.





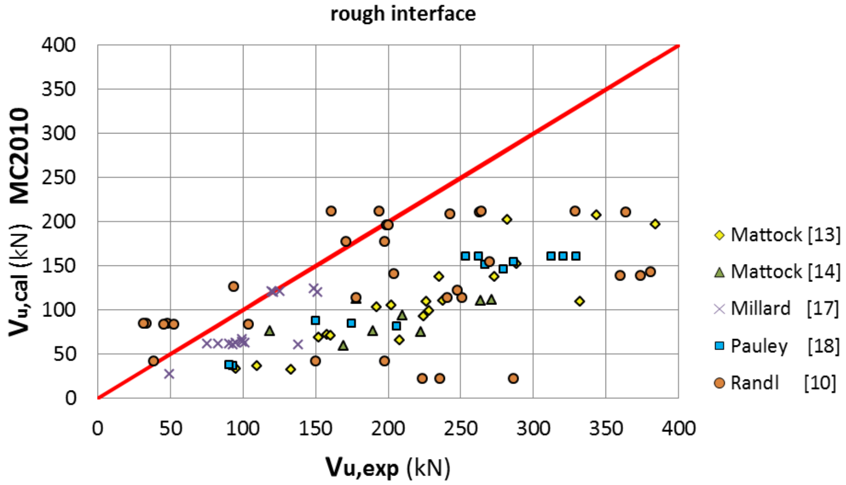
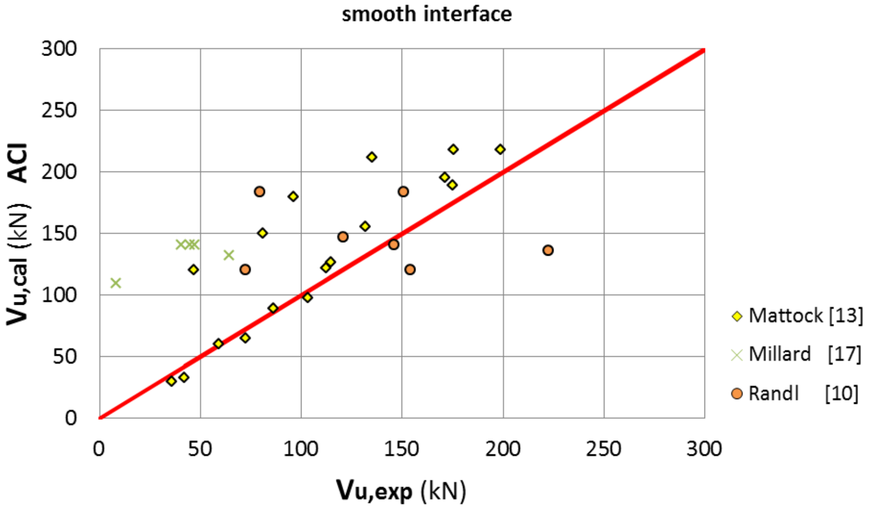
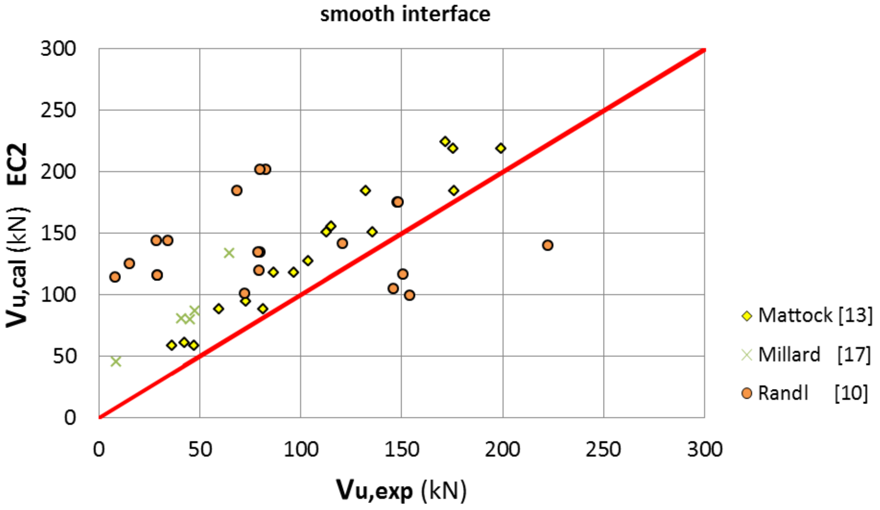


Figure 3. Rough interface resistance.





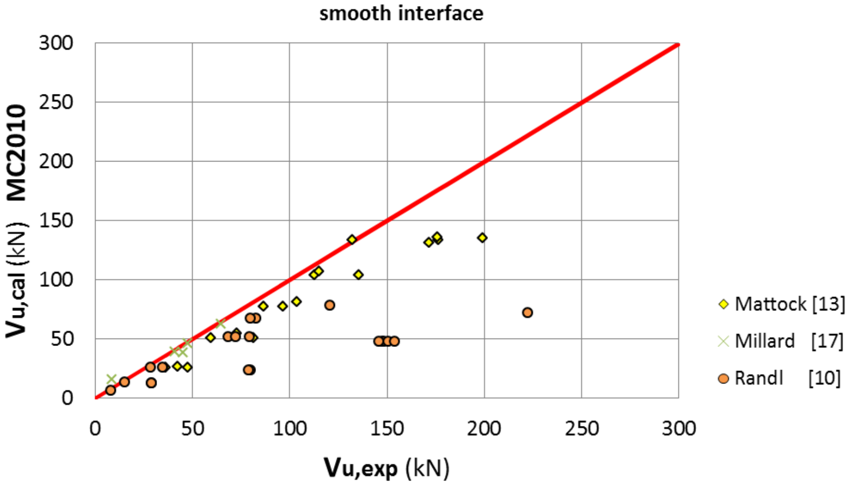


Figure 4. Smooth interface resistance.

where c,μ are coefficients that depend on the surface roughness and may be found in reference [15], α is the angle of the shear-friction steel bars and the interface, and $\nu = 0.60\cdot\left(1 - f_{ck}/250\right)$, f_{ck} in MPa, is the reduction factor for concrete strength.

According to ACI318-11 [16] the nominal shear strength of an interface in presence of shear-friction reinforcement inclined at an angle α in relation to the interface, is given by eqn (5):

$$V_n = A_v \cdot f_y \left(\mu \sin a + \cos\alpha\right) + A_c K_1 \sin^2\alpha \le \min\left[0.2 f_c A_c, 11A_c, \left(3.31 + 0.08 f_c\right) A_c\right] \tag{5}$$

where A_v is the area of the shear-friction reinforcement across the interface, A_c is the area of concrete section resisting shear transfer (mm^2) and $K_1 = 2.8MPa$ for normal concrete. The coefficient of friction, μ, for concrete placed against hardened concrete takes the values of 1.0 for surface intentionally roughened and the value of 0.6 for surface not intentionally roughened.

The MC2010 [11] expression is displayed in eqn (3).

For the evaluation of the predictions of codes Eurocode 2, ACI318-11, and MC2010 the test results of Randl [10], Mattock [13], [14], Millard and Johnson [17], and Paulay et al [18] are used, 120 specimens in all. Distinction is made between roughened and smooth interfaces, in Figures 2 and 3, respectively. The actual material strengths were used in the calculations and not the reduced (design) ones.

For rough interfaces ACI predictions offer the least scatter, while MC2010 predictions are almost all on the safe side. However, in design values are calculated, then MC2010 predictions will be in cases very conservative. For smooth interfaces, ACI and EC2 tend to be unconservative for the shear strength prediction of the test results used.

3 BEHAVIOR OF THE INFILL/FRAME INTERFACE IN RC INFILLED FRAME SPECIMENS

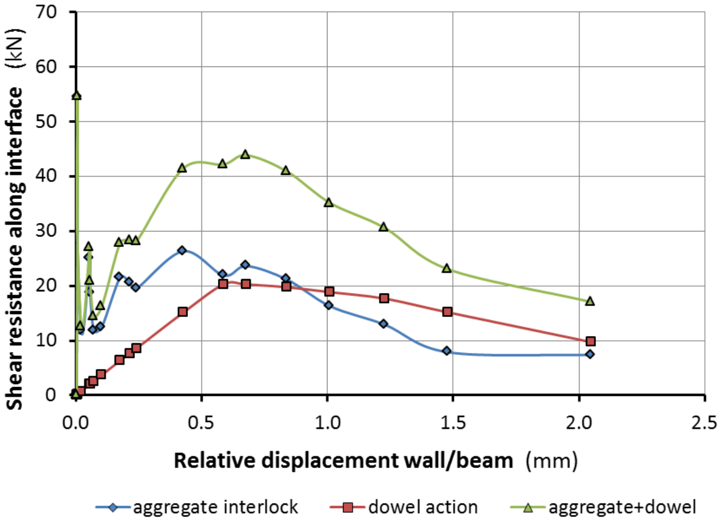
In order to simulate the behavior of the interfaces of the RC infilled frames tested in the Concrete Technology and RC Structures Laboratory in the University of Thessaly, the design expressions previously discussed were applied. In general they failed to depict the actual behavior of the specimens tested. The best approximation of the experimental behavior of the interfaces was obtained by the detailed methodolody suggested by Walraven [3].

Walraven’s model was originally developed to calculate the shear force along cracked concrete and has proved to estimate satisfactorily the shear friction resistance and the shear-slip behavior. It assumes that aggregates are spherical particles and shear resistance is based on aggregate interlock. The width of the crack is also needed for the calculations.

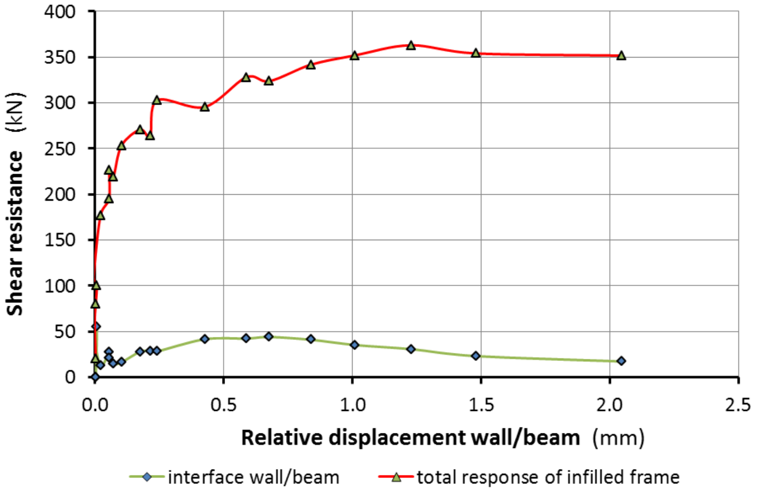
The method was applied to calculate the shear force carried at the interface through concrete, for the measured values of relative slip and detachment of the two sides of the interface. The contribution of the rebars (dowel action) was calculated by the expression proposed by Dei Poli et al. [19] (derived by the Beam on Elastic Foundation (BEF) method) for the value of relative slip measured at each loading step. The analytical prediction of the shear resistance across the interface is the sum of the shear carried by concrete plus the shear carried by dowel forces. The results are depicted in Figure 5 for specimen A7 in which the interface between wall and frame was roughened (for further details refer to [1], [2]).

In Figure 5a the calculated shear resistance along the interface is depicted against the relative displacement (slip) measured along the horizontal interface between infill wall and beam: The contributions of aggregate interlock and dowel are depicted separately. The maximum total resistance of the two load bearing mechanisms is obtained at values of relative sip about 0.7 mm.

In Figure 5b is depicted the total response of the infilled frame vs. the relative slip at wall/beam interface (experimental) together with the total calculated shear resistance of the wall/beam interface, also displayed in the Figure 5a. The contribution of the interface in the shear resisted of the infilled frame is relatively small (amounts to 15%). It is interesting to observe though that the disintegration of the interface marques also the reduction of the total response of the infilled frame, which is more obvious in other specimens without reinforcement crossing the interface. The analytically predicted shear resistance–displacement curve (V-δ) of the interface resembles the (V-δ) curve of the whole specimen. This illustrates the anticipated fact that the response degradation of the specimen’s behavior is strongly related to the degradation of the resistance of the infill/frame interface.



(a)



(b)

Figure 5. (a) Calculated resistance of the interface between wall/beam from tests
(b) Experimental total shear response and calculated shear interface resistance [1], [2]

4 CONCLUSIONS

The estimation of the interface shear transfer depends on many parameters which are difficult to quantify and predict and therefore they enclose many uncertainties. The application of test results on several design expressions has shown that the formula proposed by Randl [10], which has been adopted by MC2010 [11], guarantees safety, though in certain cases may underestimate considerably the actual shear strength. However, given the many uncertainties involved, it is judged as a prudent expression to use in general, particularly for smooth interfaces.

Application of the detailed methodology of Walraven [3] for calculating the contribution of concrete, combined to the expression of Dei Poli to take into account the contribution of dowels, resulted to a good approximation of the experimental behavior of the infill/frame interface of RC infilled frames.

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