Experimental Investigation of the Behaviour of Interfaces in RC Elements Subjected to Cyclic Actions. Effect of Compressive Stress Normal to the Interface

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SUMMARY:
In several repair and/or strengthening techniques of reinforced concrete elements, a new concrete element is added to the existing member. The behaviour of the interface between existing and new concrete may become critical under cyclic actions, reducing the connection effectiveness. This paper presents a summary of the experimental results of a research program, undertaken at the Laboratory of RC Structures, NTUA, with the purpose to systematically investigate the effect of the magnitude of compressive force normal to the interface on the behaviour of the interface, by measuring the interface slip - resistance characteristics and the force-response degradation. Artificially roughened concrete interfaces crossed by reinforcing bars (the diameter, the embedment length of bars, the way bars are anchored to concrete -by bond or using epoxy resin- the compressive concrete strength, being among the investigated parameters) are subjected to cyclic imposed shear slips, with or without the presence of compressive stress normal to the interface.
Keywords: Interface, Shear friction, Dowel action, Experimental investigation, Normal Compressive Stress.

1. INTRODUCTION

In various repair and/or strengthening techniques, in the case that the intervention consists of adding a new concrete layer or new reinforced concrete (RC) elements to the existing members of the structure (e.g. flexural strengthening of beams by adding a layer of reinforced concrete in the tensioned zone, stiffness and strength enhancement of existing RC frames by infilling entire spans with RC shear walls), the connection between the new and the old concrete has to be adequately designed and detailed. Various techniques that have been suggested and used in construction, aim to establish an improved connection between the two different layers, so that the resulting, composite, element behaves monolithically. Nevertheless, the shear load to be transferred along interfaces, depends on the measures taken to connect the old and the added concrete (use of reinforcing bars or anchors acting as dowels, roughening of the surface of the old concrete before casting the new layer, restrain of the interface) and it is a function of the shear slip along the two interfaces, a prerequisite for the mobilization of the resistance of the interface. In case of structures subjected to earthquakes, the local 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. The amplitude of shear slips to be imposed to an interface is a function of the performance level adopted for the redesign of an existing structure. Actually, if a structure has to remain practically free of damage during the design earthquake, small shear slip values along interfaces have to be taken into account. On the contrary, in structures redesigned for the performance class of life protection, extensive damages are allowed and, hence, interfaces should be designed taking into account shear slips of relatively higher magnitude.

At the same time, in the design of an interface crossed by reinforcing bars or by anchors, one cannot add 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 contribution 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 (of various performance levels) subjected to earthquakes. A series of research programs have been carried out at the Laboratory of RC Structures, NTUA, for the systematic investigation of RC interfaces within repaired or strengthened elements. These programs comprise several test series with the aim to investigate the effect of the principal governing parameters, namely concrete strength, percentage of reinforcement crossing the interface, anchorage length of reinforcing bars both sides of the interface, magnitude of the imposed cyclic slip, level of normal load on the interface etc.

In the present paper, the results of part of the tests are presented and commented upon. In this test series, the parameter considered was the presence of compressive stress acting normal to the interface.

2. 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 two main shear transfer mechanisms (namely, dowel action and concrete-to-concrete friction) have been investigated either separately or in joint action, whereas their interaction was also investigated, under mainly monotonic actions. It is to be noted that the available experimental results on the dowel action and concrete-to-concrete friction under cyclic load date back to the 70's and 80's. Repeated or cyclic shear imposed to interfaces in tests until the 80's are reported in detail in Vintzileou and Tassios (1987) and Tassios and Vintzeleou (1987). Tests on dowel action and friction were carried out, in most cases, under load-controlled conditions and, hence, cycling was limited to shear forces smaller than the maximum resistance of interfaces. Therefore, no data are available regarding the post-peak behaviour of these mechanisms.

During the last twenty years, several experimental projects investigating the cyclic behaviour of interfaces were conducted. Several parameters were studied, namely the percentage of reinforcement crossing the interface, the anchorage length thereof, the preparation of the interface as well as the compressive strength of the existing and the new concrete (Bass et al., 1989), the effect of the opening of pre-formed cracks, as well as material parameters, such as the aggregate size (Maksoud, 2002). In Nakano's and Matsuzaki's work (2004), shear friction and dowel action were studied separately for the case of interfaces between precast elements. The connections between precast elements have been the subject of an extensive experimental investigation carried out by Soudki et al. (1995a, 1995b). In order to evaluate the ACI 318-95 Shear-Friction Provisions, Valluvan et al. (1999) have tested sixteen specimens simulating the interface between old and new concrete. The dowels were set into the existing concrete into holes, using a quick-setting epoxy gel. Tassios and Vassilopoulou (2003) have modelled the shear resistance of pre-crack interfaces in reinforced concrete, based on the results of the already mentioned studies by Vintzileou and Tassios (1987) and Tassios and Vintzeleou (1987). The behavior of interfaces under monotonic and cyclic actions has been studied and modelled by Maekawa and Qureshi (1997), and Soltani and Maekawa (2008).

3. SPECIMENS AND TEST SETUP

Fig. 1a shows the geometry of specimens with embedment depth of the reinforcement normalized to bar diameter equal to 6.25, 12.5 or 20. The bars used were 8 or 12mm in diameter. The overall dimensions of the specimens were dictated (a) by the dimensions of the testing equipment used to impose shear slip along the interface (with zero eccentricity) and (b) by the need to effectively support the specimen in testing position, avoiding, however, reactions at supports that would affect the behaviour of the interfaces. Furthermore, the two concrete blocks forming each specimen were adequately reinforced aiming to avoid premature damage of the specimen outside the interface.

The specimens consisted of two reinforced concrete blocks, cast separately into metal moulds, approximately 28 days one after the other. In the present paper, test results for four (4) specimens with three bars of 8mm diameter, as well as six (6) specimens with three bars of 12mm diameter crossing the interface are presented. Besides the presence of a normal axial stress, the embedment length of the bars in the specimens was among the investigated parameter, but it was in all cases smaller than the anchorage length required for full development of the yield strength of bars (according to Eurocode 2, BS, 2004). The favourable effect of the normal stress on the interface has been apparent during previous research work (Palieraki and Vintzileou, 2011) and, therefore, further experimental results were needed to allow for a better understanding of the mechanism. In the present paper, the specimens are presented in groups of two, having the same characteristics. The only difference between the two specimens was the presence of compressive stress acting normal to the interface.

The interface was 500mm long and 100mm wide. The reinforcing bars were positioned in mid-width of the interface. Several parameters were investigated, namely the embedment length of bars crossing the interface, the roughness of the surface, the compressive strength of concrete, and mainly, as mentioned above, the magnitude of compressive force normal to the interface (see Table 1). Specimens with a limited embedment length of bars cover the (quite common) case of repair and/or strengthening techniques, where the available thickness of the existing and/or the added concrete layer does not allow for sufficient anchorage of the bars across the interface.

The clear distance between consecutive bars was equal to 20.25 or 13.7 times the bar diameter for the specimens with 8mm or 12mm diameter bars respectively (Fig.1a). S500 steel bars (mean yield strength equal to 560 N/mm^2) were used.

After concreting the first block, the interface was artificially roughened (chipped) using a pickaxe (Fig. 1b). The reinforcing bars were either (a) positioned in the first concrete block before casting of the concrete and they were protruding to a predetermined length, so that the bond with the second concrete block was also ensured, or (b) they have been positioned in the first block after drilling in the hardened concrete, anchored to place using epoxy resins. Both in the former and the latter case, in which the bars have been anchored by means of epoxy resins in the first block, these were protruding to a sufficient length in the second block, for full anchorage, so that the behaviour of the interface was governed by the behaviour of the block with the bars anchored by means of resins.

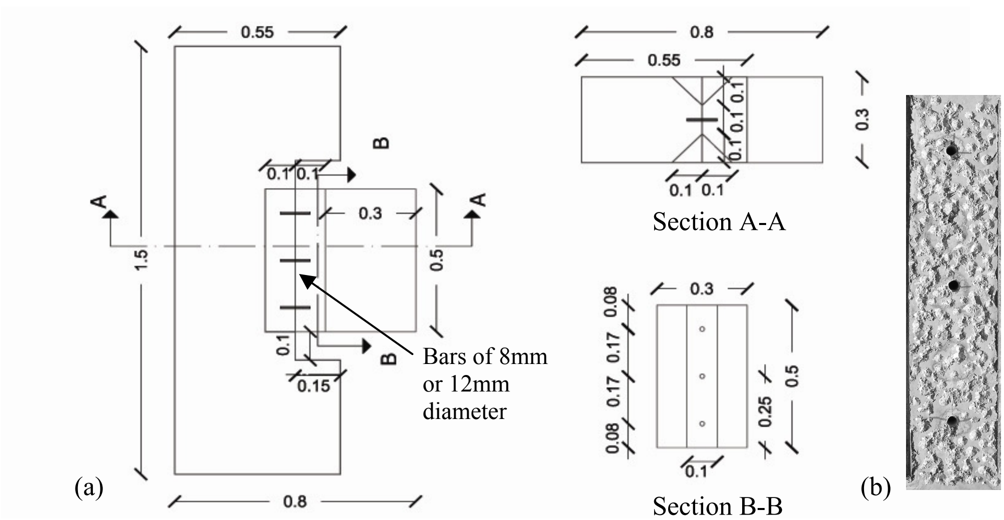

Figure 1. (a) Geometry of the specimens with three bars crossing the interface, the dimensions in meters, (b) Interface after chipping and drilling the holes, in order to place the bars by means of resins.

Table 1. Main characteristics of specimens and experimental values of maximum shear resistance of interfaces.

Specimen[1]	Number and diameter of bars/ Reinforcement ratio/ Embedment depth normalized to bar diameter	Mean compressive strength of concrete (N/mm^2)		$\tau_{u,exp}$ (N/mm^2)	corrected[2] $\tau_{u,exp}$ (N/mm^2)
		Block 1	Block 2		
N_2R-25/E/6/0.1	3Φ12/0.0068/6.25	25.06	31.10	5.04	1.91
R-25/E/6/0.1	3Φ12/0.0068/12.5	25.06	31.10	2.22	0.84
N_{1r}R-25/E/20/0.1	3Φ12/0.0068/20	25.06	31.10	4.26	1.61
R-31/E/20/0.1	3Φ12/0.0068/20	31.10	34.76	3.57	1.09
N_{1r}R-25/B/20/0.1	3Φ8/0.003/20	25.06	31.10	5.25	4.48
R-31/B/20/0.1	3Φ8/0.003/20	31.10	34.76	2.32	1.59
N_{2r}Re-21/B/12/0.1	Resins/3Φ8/0.003/12.5	25.57	21.38	4.72	4.72
Re-21/B/12/0.1	Resins/3Φ8/0.003/12.5	25.57	21.38	2.81	1.25
N_{2r}Re-21/E/12/0.1	Resins/3Φ12/0.0068/12.5	25.57	21.38	5.09	2.26
Re-21/E/12/0.1	Resins/3Φ12/0.0068/12.5	25.57	21.38	4.44	1.97

1. Designation of specimens: R: rough interface, Re: anchorage by means of epoxy resins, N_1, N_2: Normal force on the interface, equivalent to initial uniform compressive stress of 3.00 MPa or 1.60MPa, correspondingly. In most of the specimens, after the first cycle at 0.20mm the normal force was reduced, as zero force response degradation was recorded for the first value of compressive stress. In case the normal force is reduced an additional subscript "r" is added to the N_1 or N_2 designation.
The first number indicates the compressive strength of the weaker concrete block (in MPa).
B: specimens with three bars 8 mm in diameter, E: specimens with three bars 12 mm in diameter.
The second number indicates the embedment depth normalized to the bar diameter.
The third number indicates the magnitude of the cyclic shear slip imposed during the first cycle (in mm).
2. The measured maximum shear resistance is modified to account for the effect of compressive strength of concrete and the percentage of reinforcement that differs from specimen to specimen. See Section 5.2.

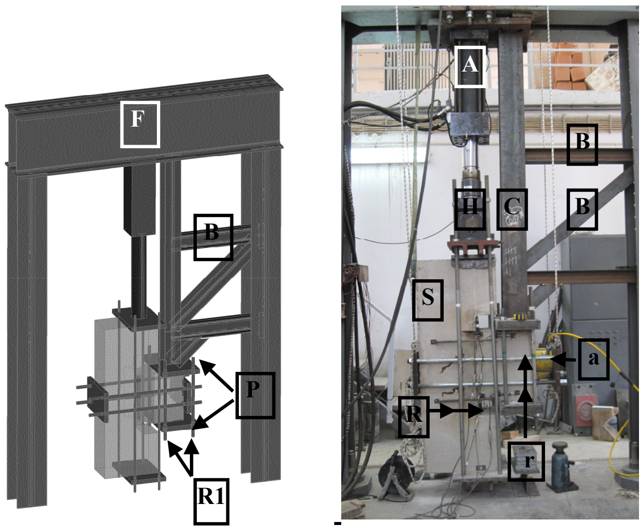

Figure 2. Test setup: (a) Sketch of the test set up applicable to specimens without normal compressive stress on the interface, (b) Photo of the test set up (specimens with normal compressive stress).

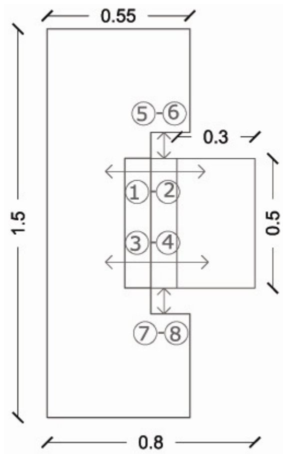

Figure 3. Position of LVDTs to measure shear slip and crack opening.

The specimens were kept wet for 2 to 3 days. Subsequently, they were stored in the Laboratory until the day of testing that took place at least one to two months after casting the second concrete block. Conventional concrete cylinders (150/300) taken during casting of each block were tested in compression the day of testing of the respective specimens. The mean compressive strength of concrete per block is given in Table 1.

Fig. 2 depicts the test setup for the last series of tests (Zeris et al., 2011), which had some small differences in comparison with the test setup used previously (Vintzileou and Palieraki, 2007, Palieraki and Vintzileou, 2009). A steel frame ("F") is anchored to the strong floor of the laboratory. An MTS actuator "A" (maximum capacity=±300kN) was placed vertically in the frame. A hinge "H" was connected to the actuator, in order to allow for the free rotation of the specimen, and to avoid damaging the actuator. The specimen “S” was attached to the actuator by means of four steel rods “R” in such a position that the piston axis coincided with the tested interface. A steel column “C” was used to keep the concrete block fixed during testing. The column “C” was reinforced against moment and buckling by means of horizontal and diagonal metal beams “B”. In order to ensure that the specimen would remain stable also for the downward movement of the actuator, the small part of the specimen (the part of “new” concrete) was kept on position using a couple of metal plates “P”, of which the upper plate was welded to the steel column “C”, while the lower plate was connected with the upper plate by means of four steel rods “R1”. Shear slips were imposed to the interface by the actuator at low speed (approx. 0.02mm/min). Where applicable, the normal compressive stress was applied to the interface by means of additional steel rods “r” and actuator “a” (max. capacity=100kN, Fig. 2a).

4. TESTING PROCEDURE

In the specimens presented here the amplitude of the cyclically imposed shear slips, during the first cycle was not an investigated parameter. Three full reversals at shear slip of ±0.10mm were imposed to the specimen. During previous investigations, it has been shown that the specimens with small embedment length cannot be subjected to cycling beyond a limit of 0.50mm, as force response degradation was exceeding 60%, or the slip at the interface was increasing without an increase of the interface resistance (Palieraki and Vintzileou, 2011). Subsequently, sets of three reversals at larger shear slip values were imposed to the specimens until the force response degradation became significant, or until the cracks formed close to the interface hindered the continuation of testing.

Fig. 3 shows the measuring devices installed to specimens. During testing, the shear slip along the interface was measured by means of four LVDTs (channels 5 to 8) on both faces of the specimen, along with the force response of the interface, whereas, four LVDTs (channels 1 to 4), placed perpendicular to the interface, measured the width of the crack at the interface level. Finally, electrical strain gauges measured the strains developed in the bars on both sides of the interface, in the course of the test. The strain gauges were glued on the two end bars crossing the interface before concreting, at a distance of approximately 10mm to 20mm from the interface, in the opposite sides of the bar.

5. TEST RESULTS

5.1. General observations

Tests have shown that the design of specimens was conservative enough to avoid any parasitic or premature cracking in places 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 equal to 0.10mm. As expected (see also Section 5.3), the behaviour of specimens with a smaller embedment length of the bars was characterized by significantly larger lateral dilatancy (i.e. transverse separation of the two concrete blocks) than for specimens with larger embedment length. On the other hand, for specimens with the same bar embedment depth (normalized to the bar diameter), the lateral dilatancy of the specimens reinforced with 12mm bars, was slightly smaller than that of specimens reinforced with 8mm bars. For the specimens with compressive stress normal to the interface, the crack opening remained in general small, given that it was prevented by the presence of the acting compressive stress. In all specimens, with the exception of two specimens reinforced with 8mm bars, diagonal cracks opened in the smaller (“new”) block of the specimen, at imposed shear slip values smaller than 0.50mm. In almost all the specimens, the smaller block exhibited the lower compressive strength and, furthermore, the cover of the reinforcement was significantly smaller. The cracks initiated from the interface (at the position of one or all the bars) and propagated at an angle of approximately 45º within the small concrete block, up to the block edge. In some cases, mainly in specimens where the embedment length of the bars was small, or the compressive strength of concrete was small, the opening of this crack did not allow the continuation of testing.

5.2. Hysteresis loops and maximum shear resistance

Fig. 4 shows typical hysteresis loops for the tested interfaces. All features that are typical for shear sensitive elements may be observed: Pronounced pinching effect associated with limited area of the hysteresis loops and a substantial force response degradation due to cycling. These characteristics become more pronounced for decreasing embedment length of the bars and absence of compressive stress normal to the interface. An additional characteristic typical for specimens with insufficiently anchored bars, the pronounced asymmetry of the hysteretic loops in the two loading directions, was not observed in the case of most of the specimens presented here. In some cases, the resistance mobilized in the second loading direction may be higher than the resistance mobilized in the first loading direction. This higher resistance was not recorded since the beginning of testing, on the contrary, it was observed when the diagonal crack at the location of the upper reinforcement bar was formed. Therefore, the unexpected behaviour can be attributed to the existence of the crack, which led to larger measured shear slip values than those actually applied on the first direction of loading.

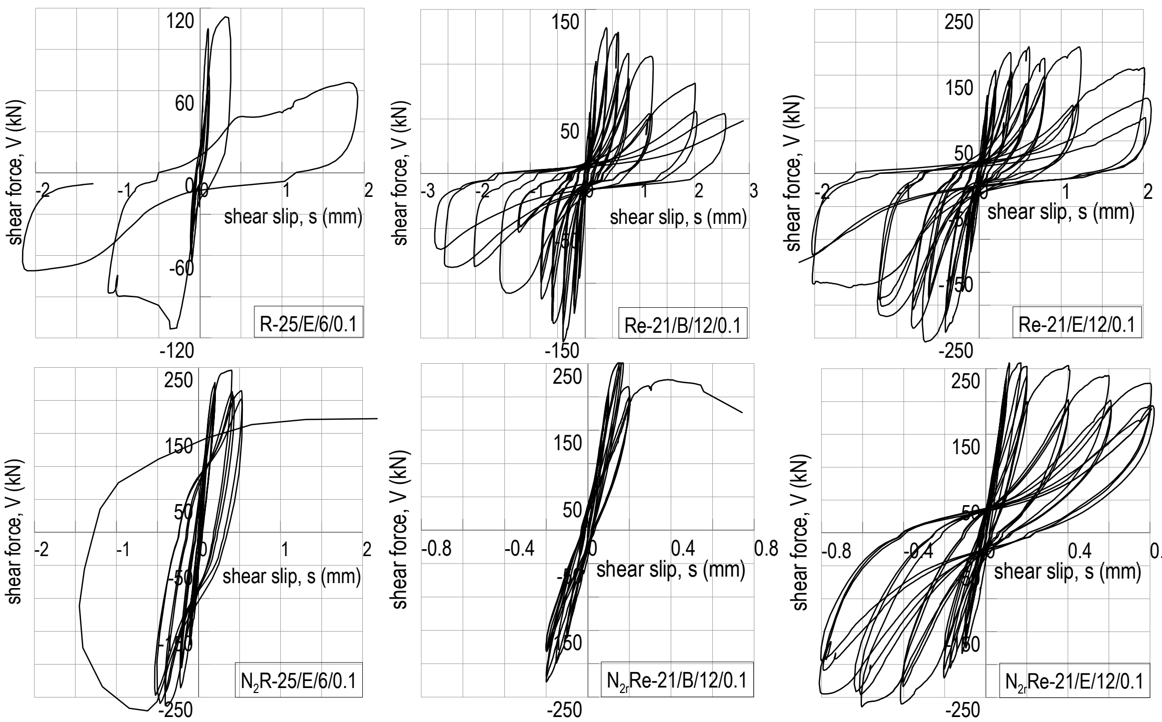

Figure 4. Typical hysteresis loops.

In all specimens, the maximum shear resistance was mobilized for slip values varying between 0.40mm and 0.60mm in the first loading direction, and for slip values varying between 0.40mm and 0.80mm in the second loading direction. The maximum shear stresses resisted by the tested specimens are listed in Table 1. It has been observed, during previous tests (Palieraki and Vintzileou, 2009) that there is an almost linear relationship between the compressive strength of concrete and the maximum shear resistance. In order to allow for a direct comparison between specimens with different embedment length of reinforcing bars, the effect of the compressive strength of concrete was eliminated by multiplying the measured maximum resistance with the ratio $21.38/f_c$, where 21.38MPa was the lowest measured compressive strength of concrete and f_c denotes the mean compressive strength of the two concrete blocks. Furthermore, given that different bar diameters have been used, the value of the maximum shear resistance of specimens with 12mm diameter bars was divided by 2.25 (namely the ratio between percentages of reinforcement for 12mm and 8mm bars respectively). It is noted that the values of the corrected resistance for the specimens with the compressive normal stress are calculated in the same way, even though in this case, the percentage of the reinforcement is significantly less important than the value of the applied compressive stress. Thus, the values of the last column of Table 1 were calculated. The values of this last column of Table 1 allow for the negative effect of reduced embedment length of bars on the maximum shear resistance, as well as the positive effect of the normal stress on the interface to be assessed. For the specimens reinforced with bars of 12mm diameter, it is observed that the corrected resistance values are smaller than those corresponding to the specimens reinforced with 8mm diameter bars. This difference could be attributed to the different failure mode of specimens with larger diameter bars; actually, in case of 12mm bars, the failure is caused by splitting of concrete and not by failure along the interface alone (as evidenced by the diagonal cracks formed in all specimens with 12mm bars).

The comparison of the corrected values of the maximum mobilized shear resistance with the results of previous research (Vintzileou and Palieraki, 2007, Palieraki and Vintzileou, 2009, 2011) shows the effect of the embedment length of the bars on the mobilised shear resistance of interfaces. Although the experimental data available for embedment lengths in the range of 20 times the bar diameter are not sufficient, it seems that the requirements of Eurocode 2 (BS, 2004) for the anchorage length requirement to fully develop the yield strength of the bars may be somehow conservative.

It is obvious that the behaviour of the specimens in which a compressive normal stress is applied is different than that of the specimens without normal stress. During the first cycles and for small values of the applied shear slip, the behaviour is almost elastic. This could be attributed to the fact that the opening of the crack was prevented by the presence of the normal stress. The degradation of the interface resistance with cycling was not important. For a small increase of the applied shear slip, the resistance reached the value of the first cycle for the smaller applied shear slip. On the other hand, it was observed that when the interface resistance reached its maximum value, in the general case, it was not possible to realize further cycles, given that a brittle failure of concrete took place with the formation of diagonal cracks of a significant opening.

In Table 2, the force response at the n-th cycle, V_n, normalized to that of the first cycle, V_1, is given as a function of the number of cycles n. The force response at each cycle is taken as the average response of the two loading directions. The force response is given for selected shear slip values. The value of the ratio V_n/V_1 depends, as expected, on the percentage of the reinforcement, on the embedment length of bars crossing the interface and on the presence of compressive normal stress on the interface. In fact, while for the specimens with larger embedment length of the bars, cycling for small amplitudes of slip (~0.10mm) led to a small decrease of the interface resistance (15-25%), for the specimen with bar embedement length equal to 6.25 times the diameter, the force-response degradation was important, even for small values of the applied shear slip (0.10mm to 0.20mm). The positive effect of the presence of compressive normal stress on the interface is obvious, even for the case of specimens for which the compressive stress was not constant, but was reduced to half of its value after an initial slip. The effect of cycling on the mobilized shear resistance is also illustrated in Fig. 5, where the hysteresis loops envelopes are shown for the first and the second loading cycles.

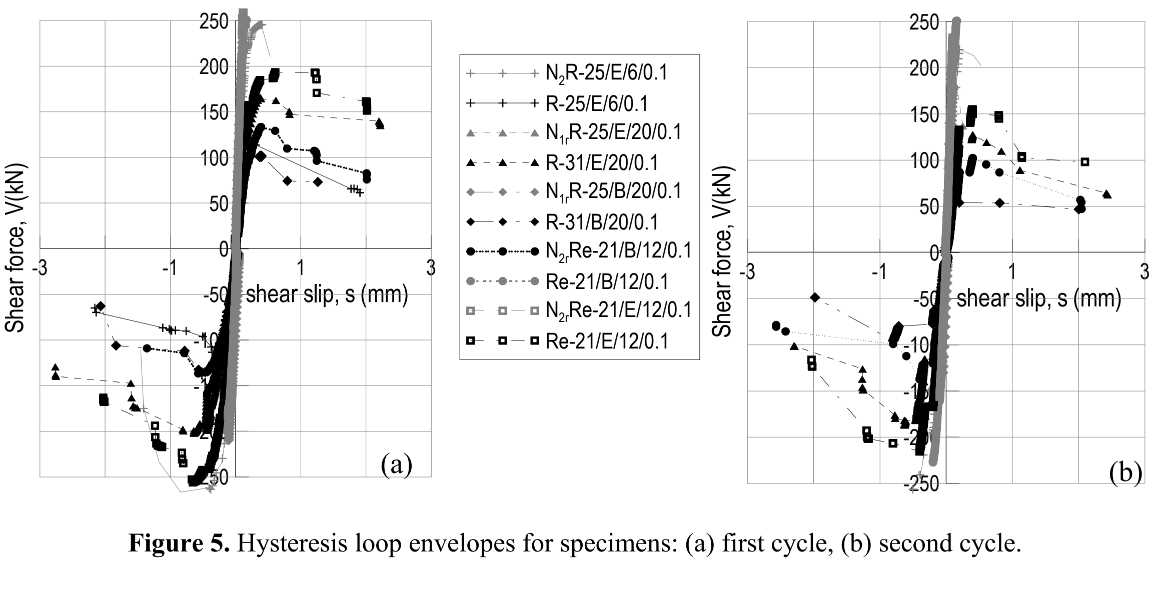

Figure 5. Hysteresis loop envelopes for specimens: (a) first cycle, (b) second cycle.

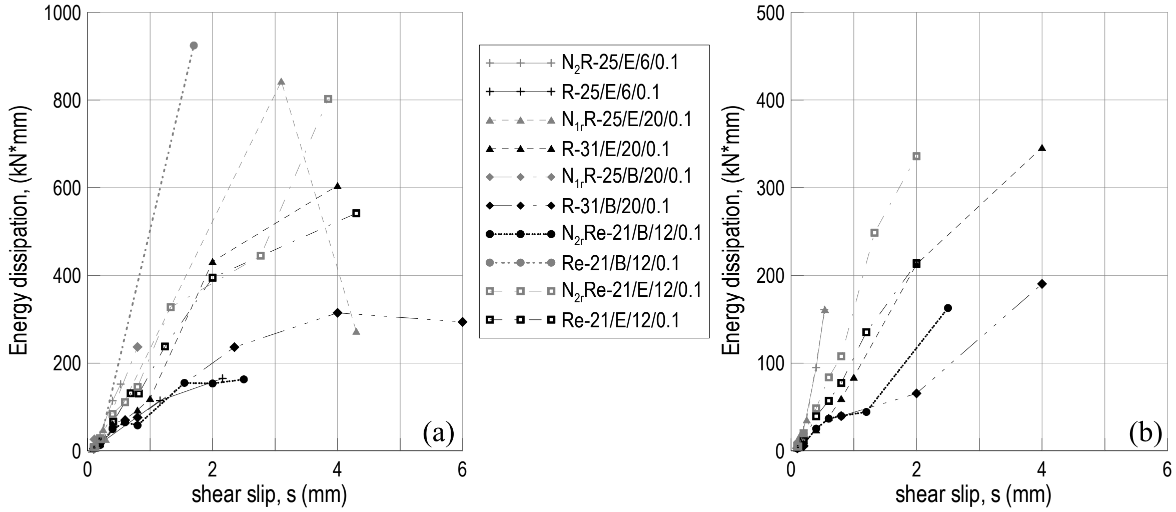

Figure 6. Energy dissipation for specimens: (a) first cycle, (b) second cycle.

Table2. Force response degradation due to cycling; V_n/V_1 values.

Specimen	s=±0.1mm			s=±0.2mm			s=±0.8mm			s=±2.0÷2.5mm		
	n=1	2	3	1	2	3	1	2	3	1	2	3
R-25/E/6/0.1	1.00	0.66	0.76	It has not been possible to realize additional full cycles.								
R-31/E/20/0.1	1.00	0.78	0.76	1.30	1.18	1.15	1.80	1.52	1.39	1.61	0.97	0.89
R-31/B/20/0.1	1.00	0.90	0.87	1.54	1.00	0.97	1.44	1.14	1.04	0.71	0.64	
Re-21/B/12/0.1	1.00	0.93	0.89	1.54	1.39	1.29	1.50	1.24	1.14	1.11	0.94	0.81
Re-21/E/12/0.1	1.00	0.94	0.90	1.42	1.24	1.22	1.74	1.50	1.44	1.42	1.00	
σ= 1.60MPa	s=±0.1mm			s=±0.2mm			s=±0.4mm			s=±0.5mm		
N_2R-25/E/6/0.1	1.00	1.05	1.04	1.58	1.42	1.42	1.74	1.55		1.62	1.53	
	s=±0.1mm (σ= 1.60MPa)			s=±0.16mm (σ= 1.60MPa)			s=±0.2mm (σ= 0.80MPa)					
$N_{2r}Re$-21/B/12/0.1	1.00	1.07	1.06	1.31	1.39	1.37	1.15	1.11	1.07			
	s=±0.08mm (σ=3.00MPa)			s=±0.14mm (σ=1.60MPa)			s=±0.25mm (σ=0.80MPa)			s=±0.5mm (σ=0.80MPa)		
N_{1r} R-25/E/20/0.1	1.00	1.57	1.72	1.70			1.63	1.22	1.35	1.94	1.58	
	s=±0.1mm (σ=3.00MPa)			s=±0.1mm (σ=1.60MPa)								
N_{1r} R-25/B/20/0.1	1.00	0.69	0.81	0.89	0.86	0.97						
	s=±0.1mm (σ=1.60MPa)			s=±0.2mm (σ=0.80MPa)			s=±0.4mm (σ=0.40MPa)			s=±0.8mm (σ=0.40MPa)		
N_{2r} Re-21/E/12/0.1	1.00	1.00	1.02	1.20	1.22	1.25	1.33	1.13	1.08	1.22	1.04	1.00
Notes: 1. The force response of the cycles at $s>s_1$ (s_1=the shear slip of the first cycle) is reported relative to the response of the first cycle at slip $s=s_1$ (σ denotes the imposed normal stress). 2. Empty cells imply that there was significant force-response degradation and the test was terminated.												

The energy dissipation in every cycle is shown in Fig. 6. Because of the increase of the applied shear slip, as well as the increase of the remaining slip along the interface, the energy dissipation increased under increasing values of the applied shear slip, while there is no decrease for large values of the applied slip, as it was observed for the force-response. The energy dissipation significantly decreased with cycling, with the highest relative decrease taking place during the second cycle, with the decrease of the force-response and the energy dissipation during the third cycle being negligible.

5.3. Crack openings and tensile strains of the bars crossing the interface

Fig. 7 shows the typical relationship between the lateral dilatancy (lateral opening of the crack along the interface) and the imposed longitudinal shear slip. The form of this diagram shows that (a) the crack opening at maximum imposed shear slip increased with the maximum imposed shear slip, but it does not always exhibit a significant increase with the number of cycles, whereas (b) the residual crack opening, at a zero imposed shear slip also increased with the magnitude of the imposed slip. For the specimens reinforced with dowels with small normalized anchorage length, there was an abrupt increase of the crack width due to the excessive pullout of the bars. This increase was not so pronounced in the case of specimens with larger embedment length. The specimens subjected to a compressive stress normal to the interface exhibited a completely different behaviour. The opening of the crack was prevented by the normal force, which also had a favourable effect on the force response of the specimen, limiting its degradation with cycling. Actually, by comparing the shear slip vs. crack width curves in Fig. 7, one may observe that in specimen R-31/E/20/0.1, a shear slip equal to 1.0mm corresponded to a crack opening approximately equal to 1.20mm, whereas for specimen N_{2r}Re-21/E/12/0.1, the same slip value caused a crack opening smaller than 0.60mm.

It should be noted at this point that this increasing residual crack opening (at zero slip) was due to: (a) the gradual smoothening of the interface that occurs with cycling, attributed to the protrusions of both aggregates and cement paste, cut during cycling, that remain entrapped in the interface and prevent the crack from closing; (b) the residual elongation of well anchored steel bars after these yield; or (c) the excessive pullout of insufficiently anchored bars.

Regarding the tensile strains recorded during testing, these also depended on the presence of compressive stress normal to the interface. The ratio of strain increase with the increase of the imposed shear slip for the specimens with normal compressive stress was quite small compared with that of the specimens without compressive stress. It is noted however, that the relative contribution of the axial strain and the dowel action (dowel deformation because of kinking) of the bars was not clear. In the case of an acting compressive stress, the bars were not free to be subjected to pullout.

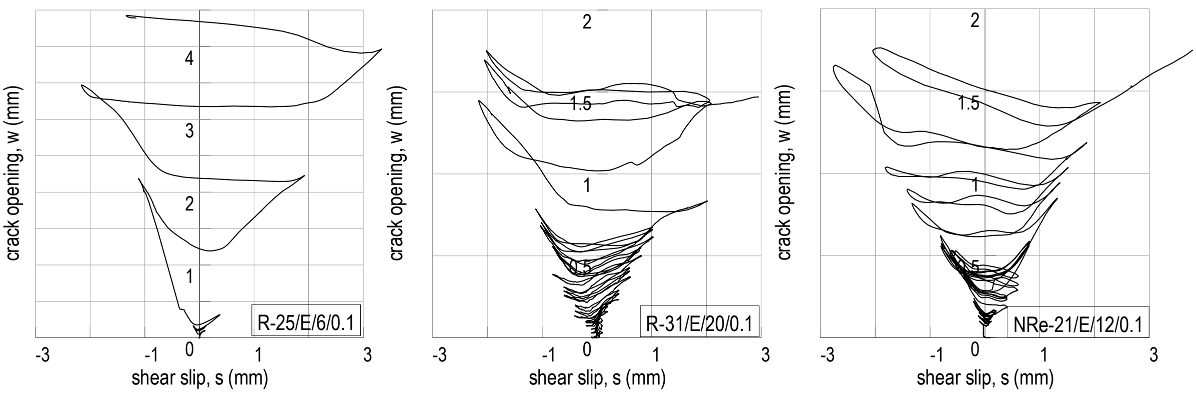

Figure 7. Typical shear slip vs. crack opening (dilatancy) curve.

6. CONCLUSIONS

The experimental results presented in this paper allow for the following conclusions to be drawn:

(1) Artificially roughened interfaces between concrete blocks cast one against the other respond to imposed shear slips by mobilizing a shear resistance which strongly depends on the embedment length of the bars. The test results indicated that there is a positive effect of the increase in the embedment length of the bars on the shear resistance of the interface.

(2) Cyclically imposed slips led to significant degradation of the shear resistance of interfaces and a pronounced pinching effect. The amount of response degradation was a function of the imposed cyclic slip, the percentage of the dowel reinforcement, the anchorage length of the reinforcing bars and the presence of stress normal to the interface; the positive effect of the latter was apparent from the test results obtained.

(3) Crack opening at the interface increased with increasing shear slip. Crack openings in the case of specimens with insufficiently anchored bars were mainly due to the pullout of the dowel bars.

(4) The tests verified the positive effect of the presence of compressive stress normal to the interface. The existence of compressive stress led to an increase in the transverse force at the interface as well as to a smaller dagradation of the response because of cycling. Finally,

(5) Further test data, obtained within the same experimental program, as well as numerical modeling of the interface behaviour, will provide sufficient data necessary for the derivation of relatively simple yet physically sound models for use in the design of interfaces subjected to cyclic actions.

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