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CYCLIC BEHAVIOUR OF INTERFACES IN REPAIRED/STRENGTHENED RC ELEMENTS

Vassiliki PALIERAKI [a], Elizabeth VINTZILEOU [b]

[a] Civil Engineer, PhD Student; Laboratory of Reinforced Concrete, National Technical University of Athens, Athens, Greece
E-mail address: *vasopal@central.ntua.gr, vasso.palieraki@gmail.com*

[b] Associate Professor; Laboratory of Reinforced Concrete, National Technical University of Athens Athens, Greece
E-mail address: *elvintz@central.ntua.gr*

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Abstract

Repair and/or strengthening of existing RC members imply, in several intervention techniques, the addition of new concrete layer(s) or new RC element(s). Interfaces, expected to transfer actions between old and new concrete, are subject to significant force response degradation when cyclic actions (due to earthquakes) are imposed to them. As a consequence, their behaviour may become critical for the effectiveness of the intervention techniques. The available experimental data regard mainly interfaces under monotonic actions; thus, they are not sufficient for the design of interfaces within RC structures subjected to earthquakes. In the present paper, part of the experimental results of a systematic program, aiming to cover all major aspects of the subject, are presented and commented upon. In the experiments presented here, interfaces between old and new concrete crossed by reinforcing bars are subjected to cyclic imposed shear slips of varying amplitude (±0.1mm to ±4.0 mm). The investigated parameters include the bar diameter and the percentage of reinforcement, the concrete compressive strength, the roughness of the interface, the level of normal load on the interface, the embedment length of reinforcing bars crossing the interfaces, as well as the bonding mechanism (either through epoxy resin or by steel to concrete bond).

Streszczenie

Poszczególne metody naprawy i/lub wzmacniania istniejących elementów żelbetowych wymagają dodania nowej warstwy betonu lub nowego elementu żelbetowego. Powierzchnie styku, które powinny przekazywać oddziaływania pomiędzy starym i nowym betonem, poddane są znacznej utracie sił przyczepności jeżeli przyłożone są do nich oddziaływania cykliczne (wynikające z trzęsień ziemi). W konsekwencji, ich zachowanie się może być niebezpieczne dla efektywności metod wzmacniania. Dostępne wyniki badań dotyczą głównie powierzchni styku poddanych obciążeniu monotonicznemu, zatem nie można ich wykorzystać przy projektowaniu powierzchni styku konstrukcji narażonych na oddziaływania spowodowane trzęsieniami ziemi. W artykule przedstawiono część wyników badań systematycznego programu, mającego na celu objęcie wszystkich głównych aspektów zagadnienia. W doświadczeniach tu prezentowanych, powierzchnie styku pomiędzy starym i nowym betonem połączone są prętami zbrojeniowymi i poddane okresowo przyłożonemu przesunięciu ścinającemu o zmiennej amplitudzie (od ±0.1mm do ±4.0mm). Badane parametry dotyczyły średnicy pręta, procentowego stopnia zbrojenia, wytrzymałości betonu na ściskanie, szorstkości powierzchni styku, poziomu obciążenia normalnego na powierzchni styku, długości zakotwienia prętów zbrojeniowych przecinających powierzchnie styku, jak również mechanizmu spajania (zarówno przez żywicę epoksydową, jak i wiązanie stali do betonu).

Keywords: **Concrete structures; Cyclic actions; Dowel action; Experimental investigation; Interfaces; Repaired/strengthened elements; Shear friction.**

1. INTRODUCTION

Interfaces between old and new concrete are typically present in existing repaired and/or strengthened RC structures. Actually, in commonly applied techniques (such as flexural strengthening of beams by adding a layer of reinforced concrete in the tensioned zone, stiffness and bearing capacity enhancement by filling spans of existing RC frames with RC shear walls, etc.), a new concrete layer or new RC elements are added to the existing members of the structure. The transfer of shear along interfaces between existing and added concrete is a prerequisite for the efficiency of the intervention and, hence, for the improvement of the behaviour of the entire structure. Although in current redesign models, repaired or strengthened elements are assumed to behave as monolithic, shear slip along interfaces is necessary for the mobilization of the resistance of the interface. The amplitude of shear slips to be imposed along 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 rather large amplitude. Needless to say that interfaces should be designed taking into account their shear resistance that is mobilized for a relevant imposed shear slip. However, the relevant resistance depends on both the amplitude of the imposed slip and the number of expected cycles.

On the other hand, when designing 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 the maximum resistance of the two mechanisms is not mobilized for the same value of shear slip.

Although, the behaviour of interfaces was experimentally investigated in numerous studies (see Section 2), the available information is not sufficient to support the design of interfaces in the case of RC structures (of various performance levels) subjected to earthquakes. The preparation of a National Code for Interventions to existing RC structures [1] has stimulated a research that was undertaken at the Laboratory of RC Structures, NTUA with the purpose to investigate in a systematic way the cyclic behaviour of RC interfaces within repaired or strengthened elements. The experimental program comprises several series of tests aiming to cover all major aspects of the subject and to investigate the effect of significant parameters, such as the percentage of reinforcement crossing the interface, the anchorage length of reinforcing bars (either placed before pouring the concrete or installed into the existing concrete and bonded by means of epoxy resin) in both sides of the interface, the imposed cyclic shear slip amplitude, the level of normal load on the interface, the roughness of the interface, etc. Numerical modelling of the behaviour of interfaces is also envisaged with the final aim to provide adequate guidance for the design of interfaces.

In the present paper, part of the experimental results are presented and commented upon. The major parameters that are investigated in the tests presented herein are the amplitude of the imposed cyclic shear slip and the anchorage length of bars.

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 of 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 monotonic actions though.

It is to be noted that the available experimental results on the dowel action under cyclic load date back to the 70's and 80's ([2], [3], [4], [5] and [6]). Moreover, as the behaviour of the mechanism was studied under load-controlled conditions, cycling was limited to shear forces smaller than the maximum resistance of interfaces. Therefore, no data are available regarding the post-peak behaviour of the dowel mechanism.

The concrete-to-concrete friction under monotonic actions was studied in numerous experimental works; the effect of parameters, such as roughness of the interface, concrete strength, the level of normal stress on the interface, the percentage of reinforcement etc., were investigated. Repeated or cyclic shear was imposed to interfaces in the tests by Colley et al. [7], Loeber [8], White et al. [9], Laible [10], Eleiott [2], Laible et al. [11], Tassios et al. [12]. As in the case of dowel action, the tests were carried out under load-controlled conditions.

In the research carried out in the last twenty years, experimental campaigns related to the cyclic behaviour of interfaces were conducted. Several parameters were studied, namely the percentage of reinforcement crossing the interface, as well as 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. [13]), the effect of the opening of pre-formed cracks, as well as material parameters such as the aggregate size (Abdel-Maksoud [14]). In Nakano's and Matsuzaki's work [15], shear friction and dowel action were studied separately, for the case of interfaces between precast elements. Tassios and Vassilopoulou [16] have modeled the shear resistance of pre-crack interfaces in reinforced concrete, based on the experimental results of the already mentioned studies by Vintzileou and Tassios [4] and Tassios and Vintzeleou [12].

Due to the specific purpose of the above researches, the experimental data are in a form that does not allow for further evaluation to serve the purpose of the present investigation.

3. SPECIMENS AND TEST SETUP

Figure 1 shows the geometry of specimens with three bars of 8 mm diameter and embedment depth of the reinforcement normalized to bar diameter equal 6.25. It should be noted that 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 to affect the behaviour of the interfaces. Furthermore, the two concrete blocks forming each specimen were adequately reinforced (Figure 2) with the aim to avoid premature damage of the specimen outside the interface.

The specimens consist of two reinforced concrete blocks, separately cast into metal moulds, approximately 28 days one after the other. Up to now, eight (8) specimens with fully anchored bars crossing the interface were tested (Vintzileou et al., [17]), as well as nine (9) specimens (Table 1) in which the bars are of limited embedment length (embedment depth of the reinforcement normalized to bar diameter equal 6.25). In the present paper the specimens with the bars of limited depth are presented in detail; comparison with the results obtained from testing specimens with fully anchored bars is also presented.

The interface is 500 mm long and 100 mm wide. The reinforcing bars are positioned in mid-width of the interface. Several parameters were investigated, namely the diameter of the bars crossing the interface, the embedment length of bars, the way in which the bars are anchored to concrete (by bond with the concrete or using epoxy resin), the roughness of the interface, the compressive strength of concrete and the magnitude of compressive force normal to the interface (see Table 1). Specimens with limited embedment length of bars cover the (quite common)

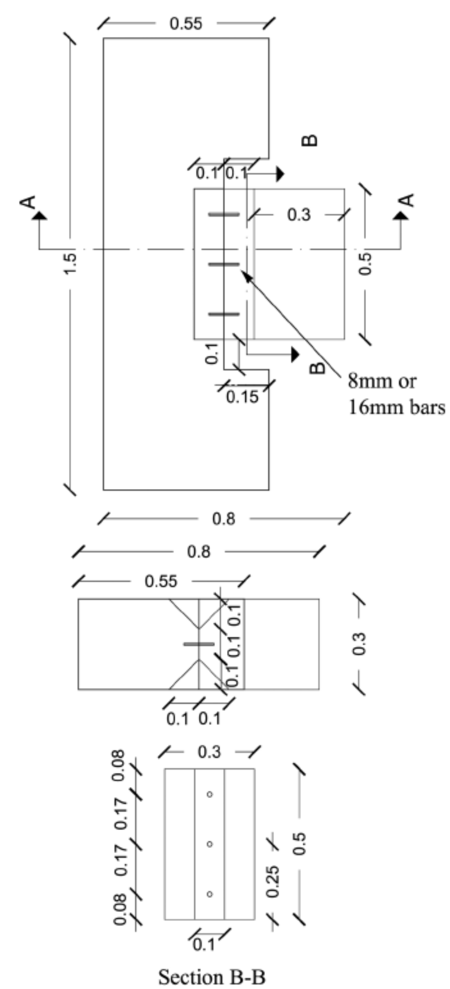


Figure 1.
Geometry of the specimens with bars of 8 mm or 16 mm diameter and embedment depth of the reinforcement normalized to bar diameter equal 6.25

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/mm²)		$\tau_{u,exp}$ (N/mm²)	corrected[2] $\tau_{u,exp}$ (N/mm²)
		Block 1	Block 2		
R-24/A/47/3.0	5Φ8/0.005/46.9	31.88	24.26	2.98	1.91
R1-24/A/47/0.5	5Φ8/0.005/46.9	31.88	24.26	3.06	1.96
R2-24/A/47/0.5	5Φ8/0.005/46.9	31.88	24.26	3.58	2.30
R-17/A/47/0.5	5Φ8/0.005/46.9	28.99	17.25	2.17	1.96
R-17/A/47/2.0	5Φ8/0.005/46.9	28.99	17.25	1.93	1.74
R-21/A/47/2.0	5Φ8/0.005/46.9	28.99	21.24	2.20	1.61
R-21/A/47/0.1	5Φ8/0.005/46.9	28.99	21.24	Unreliable force measurements	
R-24/A/47/0.1	5Φ8/0.005/46.9	31.88	24.26	2.38	1.53
R-21/B/6/0.1	3Φ8/0.003/6.25	39.74	20.98	0.55	0.68
Re-26/B/6/0.1	Resin/3Φ8/0.003/6.25	49.14	26.04	1.28	0.68
Re-27/B/6/0.1	Resin/3Φ8/0.003/6.25	36.21	27.03	4.25	3.05
R-16/C/6/0.1	3Φ16/0.012/6.25	36.00	15.94	1.25	0.51
R-23/C/6/0.5	3Φ16/0.012/6.25	38.13	22.70	2.08	0.59
R-23/C/6/0.2	3Φ16/0.012/6.25	38.13	22.70	1.87	0.53
S-17/C/6/0.1	3Φ16/0.012/6.25	33.29	17.12	1.02	0.40
S-16/C/6/0.2	3Φ16/0.012/6.25	29.67	15.57	1.20	0.50
NR-36/C/6/0.1	3Φ16/0.012/6.25	49.14	36.21	4.46	0.80

Notes:
1. Designation of specimens
R: rough interface, S: Smooth interface, Re: reinforcement anchored by means of epoxy resin, N: Normal force on the interface (equivalent to uniform compressive stress of 3.0 MPa. In specimen NRe-27/B/6/0.1 the normal force was kept constant throughout testing; in specimen NR-36/C/6/0.1, after the first cycle at 0.2mm the normal force was reduced, as zero force response degradation was recorded for normal stress equal 3.0 MPa).
The first number indicates the compressive strength of the weaker concrete block
A: Indicates specimens with five bars 8 mm in diameter, B: specimens with three bars 8 mm in diameter, C: specimens with three bars 8 mm in diameter.
The second number indicates the embedment depth normalized to bar diameter.
The third number indicates the magnitude of the cyclic shear slip imposed during the first cycle.
2. The measured maximum shear resistance is modified to account for the effect of compressive strength of concrete and percentage of the reinforcement that differ from specimen to specimen. See Section 5.2.

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 reinforcing bars across the interface.

The clear distance between consecutive bars was equal 9.62 or 20.25 times the bar diameter (Figure 1). S500 steel bars (mean yield strength equal 560 N/mm²) were used.

After concreting the first block, the interface was artificially roughened (chipped), using a pickaxe (Figure 3), either it was left as cast, in order to obtain a smooth interface. In part of the specimens, the reinforcing bars were positioned in the first concrete block before casting of the concrete and they were protruding to a predetermined length. Thus, bond with the second concrete block was also ensured. In the rest of the specimens, bars were anchored to the first concrete block after hardening (using epoxy resin). In order to test the efficiency of this type of anchorage, the bond length of those bars into the second concrete block was sufficient to ensure full anchorage capacity of the bars.

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 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 the respective specimens. The mean compressive strength of concrete per block is given in Table 1.

Figure 4 shows the test setup: A steel frame ("F") is anchored to the strong floor of the laboratory. An MTS actuator "A" (maximum capacity = ±500 kN) is placed vertically in the frame. The specimen "S" is attached to the actuator by means of four steel rods "R" in such a position that the axis of the piston coincides with the interface. Two steel columns "C" are used to keep the concrete block fixed during testing. Shear slips are imposed to the interface by the actuator, at low speed (approximately 0.1 mm/5 min). Where relevant, the normal compressive stress is applied to the interface by means of additional steel rods "r" and actuator "a" (max. capacity=100 kN, Figure 4a). The normal on the interface force is equivalent to uniform compressive stress of 3.0 MPa in the beginning of the test. In specimen NRe-27/B/6/0.1 the normal force was kept constant throughout testing; in specimen NR-36/C/6/0.1, after the first cycle at 0.2 mm the normal force was reduced to half of the value, as zero force response degradation was recorded for normal stress equal 3.0 MPa. The procedure has been repeated until the equivalent stress has been reduced to 0.3 MPa.

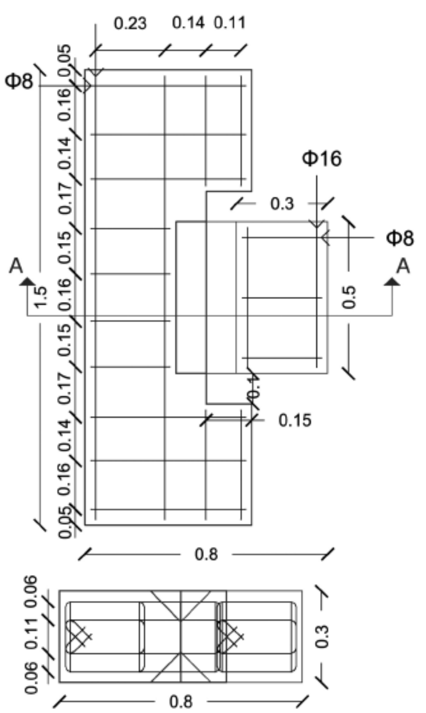


Figure 2.
Secondary reinforcement of specimens

Figure 3.
Interface after chipping 0

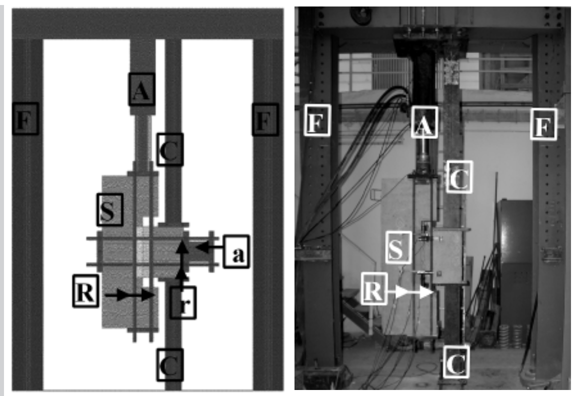


Figure 4.
Test setup: (a) Sketch of the test set up applicable to specimens with normal compressive stress on the interface, (b) Photo of the test set up (specimens without normal compressive stress)

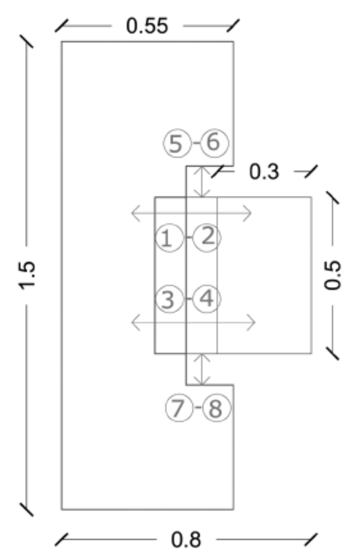


Figure 5.
Position of LVDTs to measure shear slip and crack opening

4. TESTING PROCEDURE

As shown in Table 1, one of the main parameters that were investigated is the amplitude of the cyclically imposed shear slips. A set of slip amplitudes was selected, namely: ±0.10 mm, ±0.20 mm, ±0.50 mm, ±2.0 mm. These values, in accordance with the draft

Code for Interventions to existing RC structures [1], roughly correspond to various performance levels adopted by the Code. Three full reversals at the predetermined level of slip are imposed to the specimen. Subsequently, sets of three reversals at larger shear slip values are imposed on the specimens, until the force response degradation becomes larger than 50% of the maximum response.

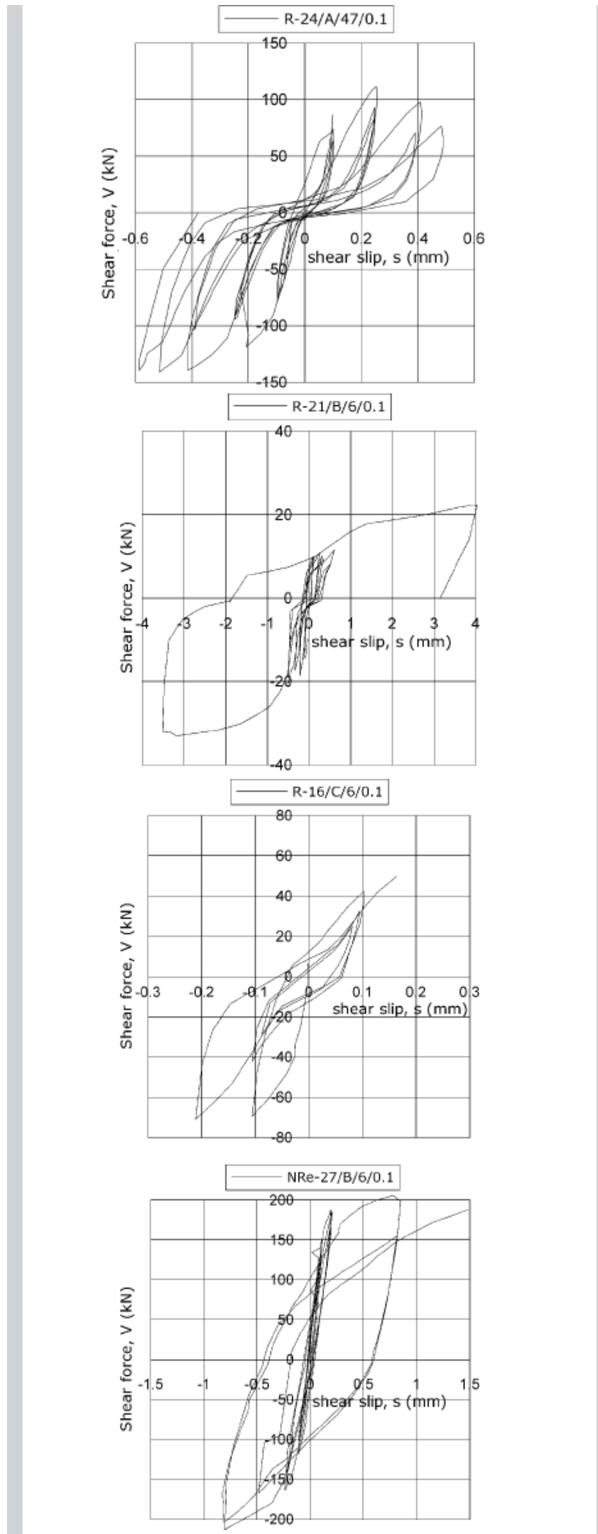
Figure 5 shows the measuring devices installed to all specimens. During testing, the shear slip along the interface is measured by means of four LVDTs (5 to 8) on both faces of the specimen, along with the force response of the interface, whereas, four LVDTs (1 to 4), placed perpendicular to the interface, measure the width of the crack at the interface level. Finally, electrical strain gauges (glued on steel bars crossing the interface before casting the concrete) measure the strains developed in the bars in the course of the test. Electrical strain gauges were glued on the two end bars in both sides of the interface. The strain gauges were positioned close to the interface (at a distance of approximately 10 mm to 20 mm).

5. TEST RESULTS

5.1. General observations

Tests have shown that the design of specimens was successful in the sense that (a) the behaviour of the interfaces was not affected by the supports of the specimens and (b) any parasitic or premature cracking in places other than along or close to the interface was avoided. Thus, in all specimens a crack opened along the interface between the two concrete blocks, at a force response approximately equal 50% of the maximum shear resistance. As expected (see also Section 5.3), the behaviour of specimens with small embedment length bars is characterized by significantly larger lateral dilatancy (i.e. separation of the two concrete blocks) than for specimens with fully anchored bars. On the other hand, specimens with 16 mm bars exhibited smaller lateral dilatancy than specimens with 8 mm bars (for the same normalized embedment length). In one case (specimen Re-26/B/6/0.1), a crack almost parallel to the interface was formed at imposed shear slip values smaller than 0.5mm, at a distance almost equal to the embedment depth of bars anchored by means of epoxy resin.

In some cases, and mainly on the specimens reinforced with 16mm bars, a diagonal crack opened in the block with the lower compressive strength, at imposed shear slip values smaller than 0.5 mm. This crack started from the interface (at the position of the bar closer to the edge of the concrete section) and propagated at an angle of approximately 45^0 within the less strong concrete block. It should be noted that the opening of this crack did not hinder the continu-



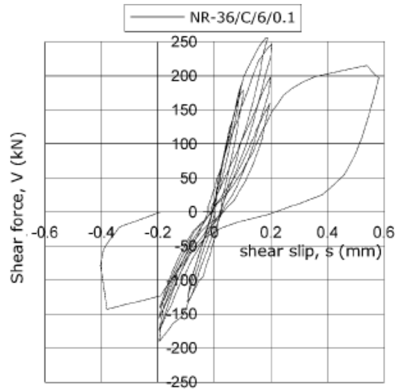


Figure 6.
Typical hysteresis loops

ation of testing in case of specimens with 8 mm bars, while in the case of specimens with 16 mm bars, failure of the weaker concrete block occurred and the test was terminated.

5.2. Hysteresis loops and maximum shear resistance

Figure 6 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 hysteresis loops and significant force response degradation due to cycling. These characteristics become more pronounced as the embedment length of the bars decreases, as well as for decreasing bar diameter. Another feature, typical for specimens with insufficiently anchored bars is the pronounced asymmetry of the hysteresis loops in the two loading directions. Actually, as shown in Figure 6 (specimen R-21/B/6/0.1 and R-16/C/6/0.1), the resistance mobilized in the second loading direction may be as low as half the resistance mobilized in the first loading direction.

In all specimens, the maximum shear resistance was mobilized for slip values varying between 0.5 mm and 1.50 mm. The maximum mobilized shear stress for the tested specimens are listed in Table 1. One may observe (see also Figure 7) that there is an almost linear relationship between the compressive strength of concrete and the maximum shear resistance. For a direct comparison between specimens with different embedment length of reinforcing bars to be made possible, the effect of the compressive strength of concrete was eliminated by multiplying the measured maximum resistance with the ratio $15.57/f_c$, where 15.57 MPa is the lowest measured compressive strength of concrete and f_c denotes the compressive strength of either the weakest block of each specimen or the block that failed (in case of bars bonded to the concrete by means of epoxy resin). Furthermore, as the specimens are reinforced either with 3 bars or with 5 bars, the shear resistance of specimens with 3 bars was multiplied by a factor equal 5/3. As long as it regards the specimens reinforced with 16 mm bars, the values of the respective maximum shear resistances were divided by a factor equal 4 (ratio between percentages of reinforcement for 16 mm and 8 mm bars respectively). Thus, the values of the last column of Table 1 were calculated. Those "corrected" shear resistance values allow for the negative effect of the reduced embedment length of bars to be detected (for example the value of the "corrected" shear resistance for specimen R-24/A/47/0.1 is equal 1.61 MPa while the value for specimen R-21/B/6/0.1 is equal 0.68 MPa). On the contrary, the positive effect of the external compressive stress on the interface is apparent (compare the values for the "corrected" shear resistance for the specimens Re-26/B/6/0.1 and NRe-27/B/6/0.1). As for specimens reinforced with 16mm bars, it can be observed that the "corrected" shear resistance values are smaller than those for specimens with 8mm bars (comparison of specimens R-21/B/6/0.1 with R-16/C/6/0.1). This could be attributed to the different failure mode of specimens with larger diameter bars, since, in this case, the failure is caused by splitting of concrete and not by failure along the interface alone.

In Figure 8, the values of maximum mobilized shear resistance, after the modification described here above, are plotted against the normalized embedment length of bars. The positive effect of increasing embedment length of bars on the shear resistance of interfaces becomes apparent. It should be noted that fresh experimental results obtained from specimens with normalized embedment length approximately equal 12.0 show that the mobilized maximum shear resistance is quite close to that mobilized when full embedment length is available, thus indicating that the required embedment length for the yield stress of steel to be mobilized is approximately equal 20.0 times the bar diameter. Further experiments are planned to check those data.

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. The force response at each cycle is taken as the average response in the two loading directions. It seems that the V_n/V_1 value depends on the imposed shear slip amplitude; it depends also on the embedment length of bars crossing the interface. Small

Table 1.
Force response degradation due to cycling; Vn/V1 values

Specimen	s=±0.1 mm			s=±0.2 mm			s=±0.35 mm			s=±0.5 mm		
	n=1	2	3	1	2	3	1	2	3	1	2	3
R-21/B/6/0.1	1	0.75		1.25	0.72		1.15	1.05		1.39	0.84	
Re-26/B/6/0.1	1	0.67	0.52									
R-16/C/6/0.1	1	0.65	0.45	1.08								
	s=±0.2 mm			s=±0.5 mm			s=±1.5 mm					
R-23/C/6/0.2	1	0.74	0.67	0.98								
S-16/C/6/0.2	It has not been possible to realize full cycles.											
	s=±0.1 mm			s=±0.2 mm			s=±0.4 mm			s=±0.8 mm		
R-24/A/47/0.1	1	0.90	0.85	1.40	1.14	1.08	1.44	1.05				
S-17/C/6/0.1	1			1.14	1.05	0.71	1.39	0.99	0.97			
σ (MPa)	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*				*3.0*	*3.0*	
Re-27/B/6/0.1	1	0.99	0.94	1.42	1.32	1.19				1.68	1.44	
	s=±0.1 mm			s=±0.2 mm			s=±0.2 mm					
σ (MPa)	3.0	3.0		3.0	1.5	0.7	0.3					
NR-36/C/6/0.1	1	1		1.37	1.35	1.14	0.97					
	s=±0.5 mm			s=±2.0 mm			s=±3.0 mm			s=±4.0 mm		
R-24/A/47/3.0							1.00	0.57				
R1-24/A/47/0.5	1	0.57	0.52	0.86	0.35							
R2-24/A/47/0.5	1	0.61	0.56	0.66	0.40							
R-17/A/47/0.5	1	0.75		1	0.67	0.51				0.85	0.68	0.50
R-23/C/6/0.5	First cycle at 0.5mm. It has not been possible to realize more cycles.											
R-17/A/47/2.0				1	0.55	0.50				0.86	0.54	0.50
R-21/A/47/2.0				1	0.56	0.55				0.84	0.52	0.46

Notes
1. The force response of the cycles at s>0.10 mm is reported to the response of the first cycle at s=±0.10 mm
2. Empty cells mean that significant force-response degradation was recorded and the test was terminated.

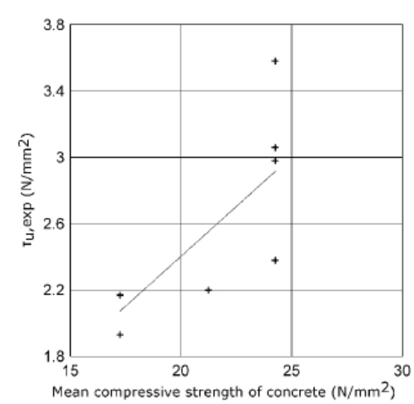


Figure 7.
Specimens with fully anchored bars. The effect of compressive strength of concrete on the maximum shear resistance

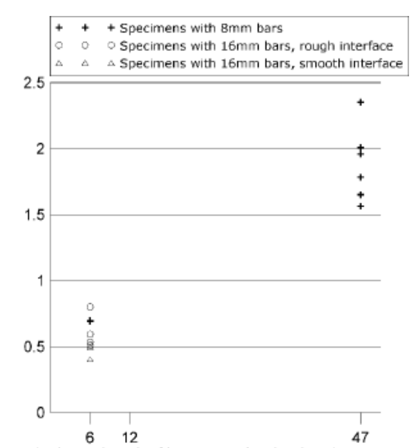


Figure 8.
Maximum corrected mobilized shear stress plotted against the embedment length of bars

anchorage of bars by means of epoxy resin seems to significantly affect force response degradation due to cycling. Actually, whereas for specimens with fully anchored bars, cycling at low slip values (~0.1mm) leads to limited force response degradation (of the order of 15-25%), specimens with normalized embedment length limited to 6.25 exhibit significant force response degradation even at slip reversals at 0.1 mm to 0.2 mm.

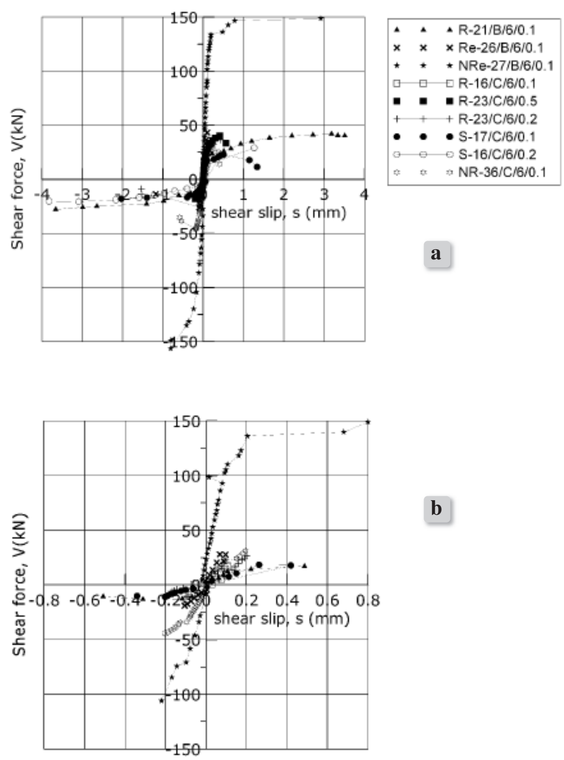


Figure 9.
Hysteresis loops envelopes for group B and group A specimens: (a) first cycle, (b) second cycle

On the other hand, the favourable effect of the normal stress on the interface is obvious. Even in case of specimen NR-36/C/6/0.1, in which the normal stress is reduced to half of its value in each cycle of 0.2 mm, the degradation of the force response is very small; in the first cycles it is even negligible. This could be attributed to the fact that the opening of the crack is prevented by the presence of the normal stress.

The unfavourable behaviour of specimens with small embedment length of bars becomes more obvious for larger imposed cyclic slips. Actually, cycling of specimens with normalized embedment length equal 6.25 was not possible beyond a limit of 0.5 mm (except for the case with normal stress on the interface), as force response degradation was exceeding 60%. The effect of cycling on the mobilized shear resistance is illustrated also in Figure 9, where the hysteresis loops envelopes are shown for the first and the second loading cycles. For the specimens not shown in Figure 9b, it has not been possible to perform a second slip reversal. It can also be observed that the behaviour of specimens belonging to groups A and B (reinforced with 8 mm bars) seems to be more ductile than the behaviour of the specimens of group C (16mm bars). This can be attributed to the failure mode, caused by the failure of concrete and not the failure of the reinforcement.

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

Figure 10 shows a typical relationship between the lateral dilatancy (opening of the crack along the interface) and the imposed shear slip. The form of this diagram shows that (a) the crack opening at maximum imposed shear slip increases with the maximum imposed shear slip, but it does not always present an important increase with the number of cycles (e.g. specimen R-23/C/6/0.2), whereas (b) the residual crack opening, at zero imposed shear slip, also increases with the magnitude of the imposed slip. For all specimens tested in this part of the experimental program (Groups B and C), there is an abrupt increase of the crack width due to the excessive pullout of the bars. The only specimens that exhibit completely different behaviour are specimen NRe-27/B/6/0.1 and NR-36/C/6/0.1 (specimens with normal interface stress). In those specimens, the opening of the crack is prevented by the normal force, which has also 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 for specimens R-23/C/6/0.2 and NRe-27/B/6/0.1, one may observe that in specimen R-23/C/6/0.2, a shear slip equal 0.5mm corresponds to a crack opening approximately equal 1.00mm, whereas for specimen NRe-27/B/6/0.1, the same slip value causes a crack opening smaller than 0.20mm. Even though further experimental results are needed to allow for quantification of the effect of the normal compressive stress on the behaviour of interfaces, its positive effect is apparent.

It should be reminded here that the increasing residual crack opening (at zero slip) is due (a) to the smoothening of the interface that occurs with cycling: Peaks of both aggregates and cement paste cut during cycling remain entrapped in the interface and they prevent the crack from closing, (b) to the residual elongation of well anchored steel bars after they yield or (c) to the excessive pullout of insufficiently anchored bars.

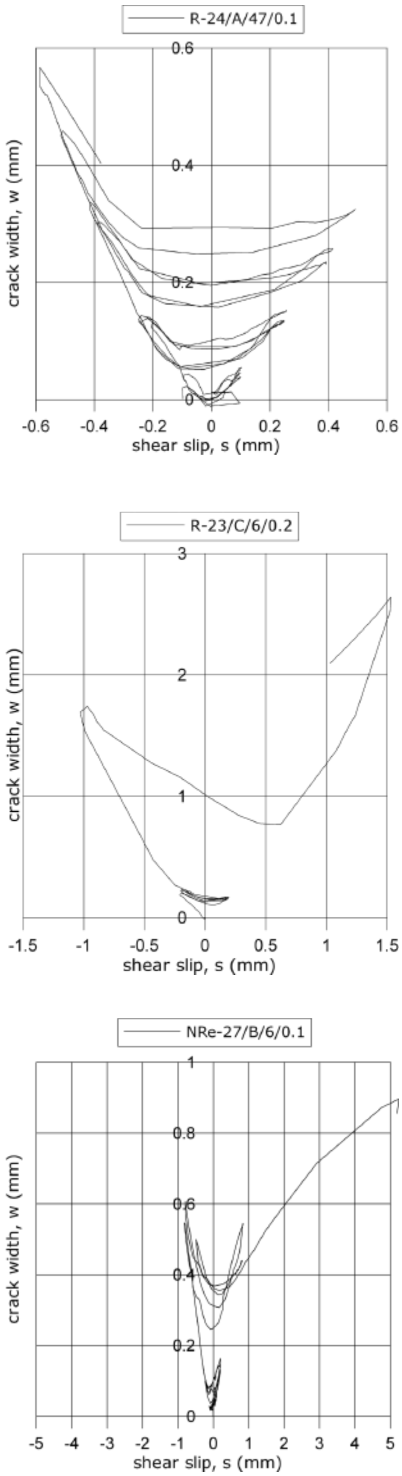


Figure 10.
Typical shear slip vs. crack opening curve

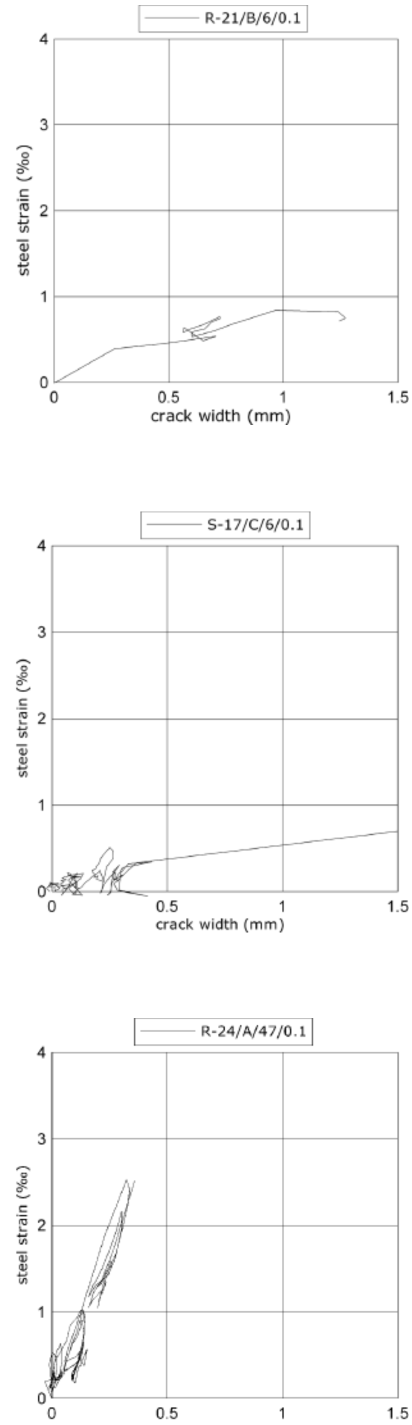


Figure 11.
Mobilization of steel strain as a function of crack opening

It should be noted, that due to the limited embedment length of bars, the tensile strains recorded during testing are rather small. The rate of steel strain increase with increasing crack width is quite small, when compared to that of bars with sufficient anchorage length. Let us compare, for example, the specimens shown in Figure 11: For imposed slip almost equal 0.50mm, the bars crossing the interface of specimen R-24/A/47/0.1 have yielded, whereas the bars crossing the interface of specimen R-21/B/6/0.1 and specimen S-16/C/6/0.1 are under a tensile strain not exceeding 0.0005.

5.4. Analytical modelling of interfaces

Although testing campaign is still in progress, analytical modelling of interfaces was initiated. For this purpose, the computer code MASA, developed at the University of Stuttgart (information regarding the code can be found in the web-site of the university: http://www.iwb.uni-stuttgart.de/forschung/masa/MASA_en.htm, as well as in many papers), is applied. The program is primarily intended for use in nonlinear analysis of concrete and reinforced concrete (RC) structures in the framework of local or non local continuum theory, where damage and fracture phenomena are treated in a smeared way (smeared crack approach) (Ožbolt et al., [18]). The application of the computer code seems to yield very promising results (Figure 12).

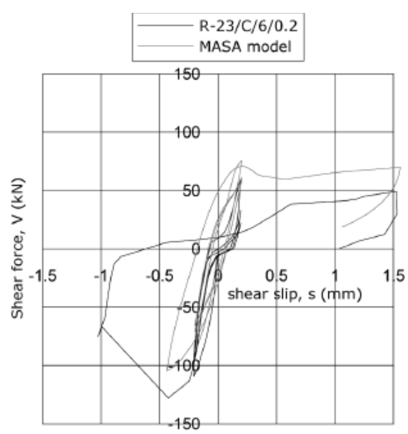


Figure 12.
Typical hysteresis loops for specimen R-16/B/12/0.2. Comparison between experimental results and analytical predictions

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 resistance, which depends strongly on the embedment length of the bars. The positive effect of increasing embedment length of the bars on the shear resistance of interfaces has been observed.

(2) Smooth interfaces can also mobilize significant resistance.

(3) Cyclically imposed slips lead to significant degradation of the shear resistance of interfaces. The amount of response degradation is a function of both the imposed cyclic slip and the anchorage length of the reinforcing bars.

(4) As expected, crack opening at the interface increases with increasing shear slip. It has been observed, that crack openings in case of specimens with insufficiently anchored bars are mainly due to the excessive pullout of the bars.

(5) Due to the limited embedment length of bars, the tensile strains recorded on the bars during testing, are rather small.

(6) Even though further experimental results are needed to allow for quantification of the effect of the normal compressive stress on the behaviour of interfaces, its positive effect is proven by experimental results obtained so far.

(7) Further experimental data to be obtained within the same experimental program, as well as numerical modeling of interfaces (the application of computer code was initiated and seems to yield very promising results) will serve the need of deriving simple enough and physically sound models for the design of interfaces subjected to cyclic actions.

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