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IMPACT OF SURFACE ROUGHNESS ON THE DEBONDING MECHANISM IN CONCRETE REPAIRS

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Abstract: Surface roughness of the existing concrete substrate was considered to have the greatest impact on the bond strength in repair systems. However, the influence of this parameter has been subject for debates in recent years. The effect of concrete surface roughness is not quite clear, nor there exist a clear relation between the surface roughness and the adhesion in multilayer systems. In order to understand and explain this relation, simple numerical experimentation is used. Repair systems with different roughness parameters are simulated in order to get load displacement diagrams and crack debonding propagation. The influence of roughness on the composite response in simulated direct tension, shear and three point bending test using a lattice model, is studied. Results indicate that roughness has different influence on tensile and shear bond strength. In addition, although it seems to have negligible influence on load bearing capacity of the composite system in bending, it enables more monolithic response and slower debonding propagation.

1 INTRODUCTION

Very important step in achieving reliable and durable repair of concrete structures is appropriate surface preparation of the old concrete. Removing impurities from the surface, adequate roughening and moisture preconditioning are inevitable steps in substrate preparation before casting repair material.

Surface roughness used to be viewed as the governing parameter affecting the bond strength in multilayer systems. This was mainly attributed to the increase of the contact area and mechanical interlocking between the two materials. However, bond tests [1] suggest that roughness has no relevant effect on the bond strength. Bond strength in rough and smooth surfaces, prepared by water jetting and sandblasting, respectively, was approximately equal. Yet, the interface failures were more frequent on sandblasted surfaces. Similar observation was made in [2], where optical profilometry measurements were performed on the substrate section before and after the direct tension test to quantify the surface roughness. It was shown that for rougher surface, failure zone does not follow the physical interface between the two materials. Higher roughness led to less repair mortar and more aggregates from concrete substrate at the fracture surface. Cores for this tension testing were taken from the edge of the composite beams. The beams were exposed to static and cyclic loading when deflection and crack propagation were measured to evaluate structural behaviour of the composite system. Debonding length in each specimen after failure in three point bending test was measured. This way results obtained from bond strength testing of cores were compared to structural behaviour of each bond. Specimens with smooth surface had much higher length of debonding compared to those with rougher surface, even though the bond strength of the specimens with smooth surface was substantially higher. It was concluded that roughness does not enhance bond strength directly but that it enables monolithic behaviour of the multilayer system and lowers the probability of debonding. Also, in inadequately roughened concrete substrates, with low level of restrain, shrinkage of the repair material may cause significant reduction of the bond strength and result in total debonding [3].

However, it is possible that surface preparation can have some negative effects as well. In [4], it was noted that some of the impacting methods for surface preparation, such as jack hammering, can induce microcracking and surface damage which "easily outweighs the benefits of an increased roughness". Other research [5] indicated that influence of roughness cannot be explained just on the basis of mechanical interlocking. They stated that increased roughness may influence the ability of the repair material to penetrate into cavities of the old concrete. Further on, smoother surface (obtained by polishing) appeared to have higher capillary absorption close to interface and therefore enabled better development of mechanical and chemical anchorage between the two materials, which resulted in stronger bonding.

These differing opinions regarding the influence of the substrate roughness can be attributed to the complexity of the problem. Debonding mechanism and bond strength in concrete repairs depend on a variety of material parameters and environmental conditions [6]. These factors are interdependent, and it appears very difficult to experimentally separate one and independently observe its influence.

That is why the use of a numerical simulation is valuable and beneficial, enabling the insight on the influence of just one parameter while keeping the others constant. Therefore, this paper tends to explain the influence of the surface roughness of the concrete substrate on the mechanical bond properties in the repair system through numerical experimentation. Repair systems with different roughness parameters are simulated in order to get load-displacement diagram and debonding propagation. For the simulation, the lattice model is used.

2 BOND STRENGTH TEST METHODS

According to the European Standard [7], bond is defined as the adhesion of the applied product or system to the concrete substrate. A wide range of possible test set-ups have been developed and used for laboratory testing of the bond strength. These tests should be selected such that they represent the state of the predominant stresses that the structure is exposed to in the field [3, 8]. Common bond test methods include interface shear, torsion and tensile test. Interface strength values obtained in these tests vary substantially as the measured properties are greatly dependent on used test method, test set-up, specimens size, loading rate, etc.

Although numerous different testing procedures are used, little information is available on comparison of these test methods and the resulting bond strength values [8]. Since shear and tensile bonding mechanisms have substantially different characteristics, relating them is quite difficult. Nevertheless, some researches [9-11] indicated a correlation between the two test methods. Tensile strength of an interface between cement-based materials is at the most 50% of its shear strength [1, 11].

Understanding of bond mechanism must include information of the weakest link in composite member. While determining bond strength, location of failure is usually defined as "substrate", "interface" or "overlay". But, exact location of fracture, especially for "interface" type failure, is not examined. In addition, interface failure per se, (i.e. without partial fracture in substrate or overlay) is unlikely to occur [3]. Therefore, analysis of fracture pattern and fracture behaviour, both before and after crack localization, is essential for understanding the bonding mechanism. This is particularly important for estimating the influence of surface roughness as it may have the crucial influence between debonded area after reaching peak strength when remaining stress-transfer occurs through crack-face bridging and friction between the cracked faces.

In order to understand and explain the influence of surface roughness on the bond strength values obtained in different test methods, numerical experimentation is used. Repair systems with different roughness parameters are simulated in order to get load displacement diagram and crack pattern. The influence of the roughness on the composite response in simulated direct tension, shear and three point bending test is done using a 3D lattice model. In the following, the background of the model is briefly presented.

3 LATTICE MODEL

Fracture processes of cement-based materials can be simulated very successfully with lattice models [12-14]. In these model material is schematized as a network of truss or beam elements connected at the ends. All the single elements have linear elastic behaviour. In each loading step, an element that exceeds limit stress or strain capacity is removed from the mesh. The analysis procedure is then repeated until a pre-determined failure criterion is achieved. In this way realistic crack patterns can be obtained. Further on, although each element has brittle behaviour, structural softening and ductile global behaviour can be simulated.

In the model presented here, all the beams have the same cross section. Diameter of the beam is chosen to be 0.5 of cell size (voxel size in 3D) [14]. Disorder in the material is implemented by using random orientation of the elements. Further work will consider also the material heterogeneity of concrete, by taking different material properties of aggregate, interface, and cement matrix into account.

The procedure to generate the network is as follows:

- A cubical grid is chosen.
- In each cell of the square (cubical for 3D lattice), a random location for a lattice node is generated. This means that some disorder is built into the lattice.
- Always the three nodes (four nodes for 3D) which are closest to each other are connected by beam elements.
- The beams which belong to each phase are easily identified by overlapping material distribution on top of the lattice. Interface elements are generated between concrete substrate nodes and repair material nodes. In figure 1, generation of interface elements for the smooth and rough surface is presented.
- The elements in the repair material, concrete substrate and interface are ascribed different mechanical properties, as indicated in Table 1.
- Elements can fail either in tension or in compression, when the stress exceeds its strength. For the fracture criterion, only normal forces are taken into account to determine the stress in the beams.

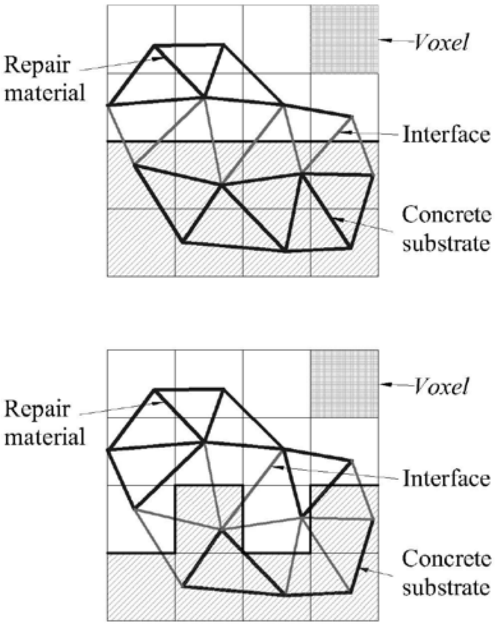

Figure 1: Two-dimensional overlay procedure for smooth and rough surface (gray – concrete substrate, white – repair material)

Values of mechanical properties in Table 1 are just assumed values and should be calibrated with experimental results. As interface is the weakest zone in the system, lower properties are ascribed to elements which characterize this zone. For simplicity, it was also assumed that the repair material has the same mechanical properties as the concrete substrate. In real repaired systems, this is not the case. This was done in order to avoid additional influence of this parameter on the response of the system.

Each of the nodes in 3D system has 12 degrees of freedom. The 3D composite system is modelled with 10800 nodes and 77216 elements for tensile and shear test, and with 8640 nodes and 60705 elements for three point bending test. Linear dimension of a voxel is 1 mm. Influence of the mesh size on the obtained results will be studied in later stage.

Table 1: Input values for the beam elements in the simulation

	E (GPa)	ft (MPa)	fc (MPa)
Repair material	30	3.25	-32.5
Interface	25	1	-10
Concrete substrate	30	3.25	-32.5

4.1 Generating surface roughness

Three different types of surface roughness profiles are imitated in order to simulate the roughness that is usually prepared in experiments (Figure 2).

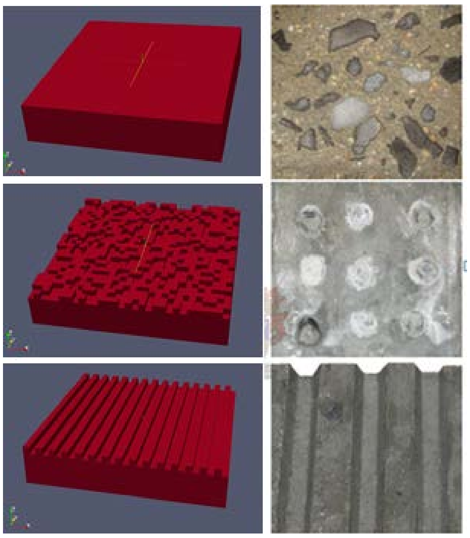

Figure 2: Simulated surface profiles compared with experimental preparation (1-smooth surface, 2-chip and 3-groove roughened)

Further on, height (h_g) and length (l_g) of the grooves for the type 3 profile in Figure 2 are varied. This was done in order to see how the roughness parameters in simulated concrete substrate affect bond strength values and debonding propagation in simulated tests.

Based on experimental results for measuring surface profile of the concrete substrate, several parameters can be defined to quantify the surface roughness [15-17]. Since very simplified surface profile is simulated, only the average profile R_a [mm] is relevant here and is used for amplitude parameter. It is defined as the mean value of the local profile z_i [mm]:

$$R_a = \frac{1}{n}\sum_{1}^{n} z_i \tag{1}$$

where n is the number of local profiles.

Slope parameter is also introduced in order to quantify the slope of the profile and repetitiveness within sampling length. The root mean square of the profile within the sampling length, R_s [mm] is defined as:

$$R_s = \sqrt{\frac{1}{N}\sum_{N}\left(\frac{\Delta z}{\Delta x}\right)^2} \tag{2}$$

where N indicate the number how often profile crosses certain threshold in specified length (for the threshold here, R_a value is chosen).

Varied parameters and average roughness profile for each simulated surface roughness are presented in Table 2 and Figure 3. If compared, GR3 and GR4 represent lower frequencies roughness with the same amplitude parameter of GR1 and GR2 respectively.

Table 2: Roughness parameters for the simulation

Surface profile	R_a [mm]	R_s [mm]
GR1	0.5	0.186
GR2	1	0.371
GR3	0.5	0.111
GR4	1	0.222

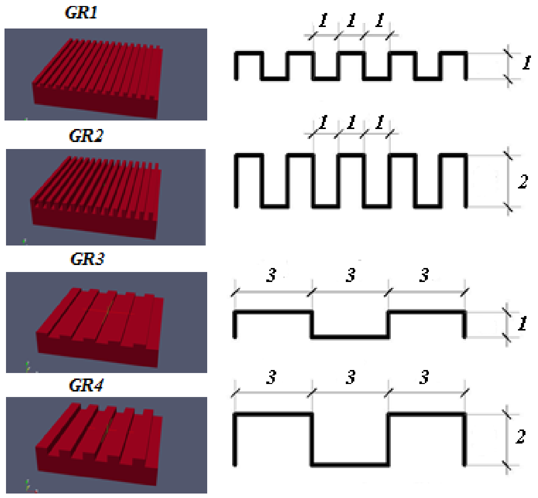

Figure 3: Varied surface profiles for groove roughened surfaces [mm]

4 SIMULATIONS AND DISCUSSION

Direct tension test and shear test are commonly used to determine bond strength and properties at the interface of two materials. Three point bending test is used to examine structural behaviour and deboning tendency of the composite system. That is why these three tests (Figure 4) were simulated by the lattice model presented earlier. The aim was to determine and explain the influence of the roughness parameter on the bond strength values obtained in each simulated test. The input parameters for all three simulations were the same (Table 1), except for the dimensions of the specimen for three point bending test.

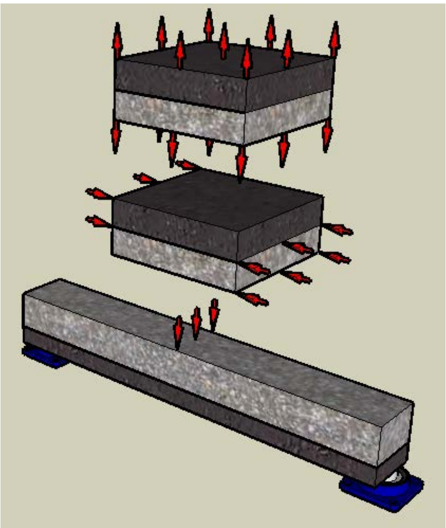

Figure 4: Set-up for the tests (direct tensile test, shear test and three point bending test)

Cross section of the specimens for direct tension and shear test are 30×30mm with the height of 12mm. The dimension of the beam specimen for bending test is 12×12×60mm.

4.1 Direct tension test

The specimen in direct tension test was loaded by prescribing the vertical displacements at the upper and lower edge (Figure 4). Rotations and in-plane translations at the specimen edges are restrained. The stress displacement curves for rough and smooth type of surface preparation (Type 1 and 2 from figure 2) are plotted in Figure 5.

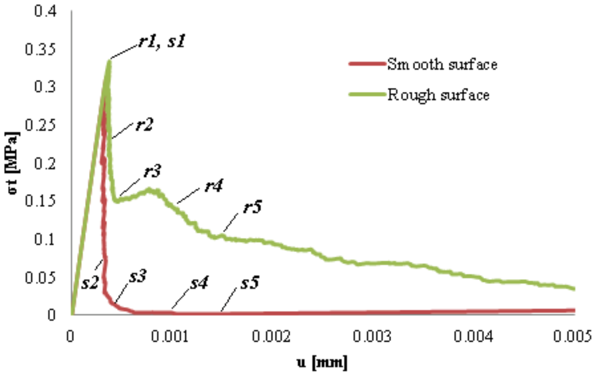

Figure 5: Tensile stress vs. vertical (opening) displacement for rough and smooth surface

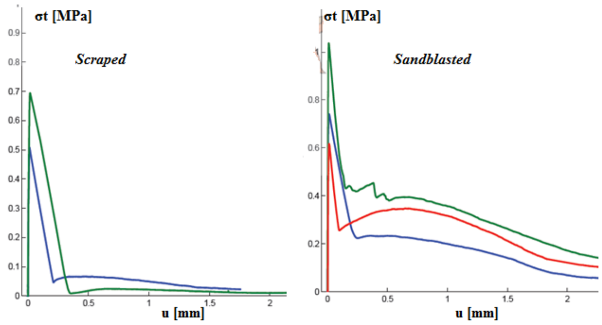

Figure 6: Experimental results for direct tension test [18]

Results obtained in simulation show a tendency similar to experimental results obtained in [18] (Figure 6). There, a direct tension test was chosen for measuring the adhesive strength and fracture energy of the interface in a composite system prepared with concrete and Engineered Cementitious Composite (ECC). The cross section of the system was 130×100 mm with the height of

200mm. Figure 5 shows results for scraped and sandblasted specimens. Scraped surface has a relatively smooth profile differing from sandblasted specimens with relatively rougher surface profile.

Although absolute values from the experiment and simulation cannot be directly compared because of the different specimen dimensions and testing set-up, the shape of the diagram shows the same trend. Specimens prepared by sand blasting need greater tensile fracture energy to break. From a purely mechanical point of view, this can be explained by presented simulations.

In Figure 5, the points are chosen for which the snapshots of the crack history are made. These are given in Figure 7.

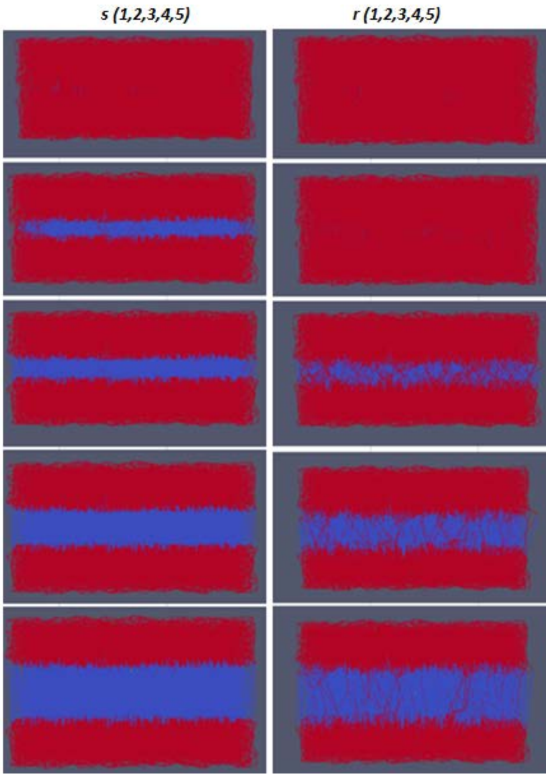

Figure 7: Debonding history of simulation of uniaxial tensile test for smooth and rough surface (blue elements represent the crack)

As the interface elements have the lowest properties (tensile strength and E modulus), a crack starts initiating at the interface. Debonding starts to develop uniformly through the whole interface area and localizes after peak loading. Crack initiation does not start from the edges. This can be due to small height of the specimen, and fact that no initial notch nor heterogeneities (except for geometrical) are ascribed in the model. As a consequence, there is no bending developing in the specimen.

Considering tensile strength of the system, it seems that the rougher surface has a negligible effect. Rough surface shows to have 6% higher tensile strength than smooth surface. Similar tendency was indicated in [8] In Figure 8, results of the maximum force for the each simulated specimen are shown.

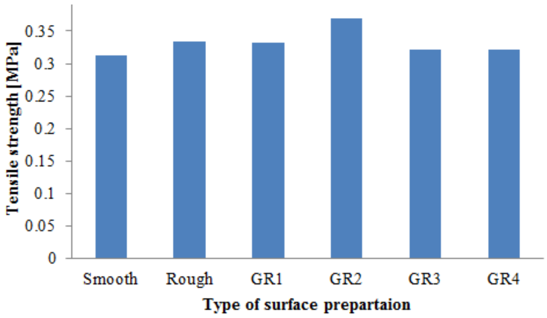

Figure 8: Calculated tensile bond strength of the different substrate roughness

While higher roughness does not seem to effect substantially the bond strength itself (i.e the peak load achieved is roughly the same), it certainly does affect fracture propagation and post-peak behaviour. Smooth surface shows more brittle post-peak behaviour and needs less fracture energy to break. Nearly all the interface elements break at the same time and debonding occurs very fast. On the other hand, rough surface seems to enable higher ductility and more stable fracture of composite system loaded in direct tension. Therefore, differences in surface roughness seems to considerably affect stress-strain diagrams and fracture behaviour of the system. These diagrams, for specimens with varied roughness parameters, are shown on the Figure 9.

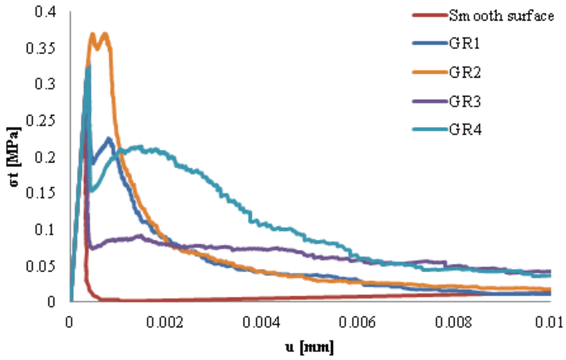

Figure 9: Stress-displacement curve for varied roughness parameters

It can be noted that surface GR3, with lower slope parameter and shallower groove behaves similar to smooth surface, and that by increasing depth of the groove, ductility in the direct tension increases and more energy is needed for breaking all the interfacial elements. Situation of simulated roughness GR2 is nearly impossible to obtain in practice. To achieve this geometry is very difficult. It would also demand substantial workability of the repair material to penetrate into these cavities. Furthermore, a lot more friction between two inclined surfaces would occur, and, theoretically it would present more shearing type of action in between fringes, than direct tension. As a result of this high shearing friction in between fringes, bond strength for GR2 is substantially increased (Figure 7).

Results obtained from the model can be explained by higher probability of beam elements on the interface to be aligned more horizontally (i.e. perpendicular to the direction of the applied force) in case of rough surface configurations (Figure 10).

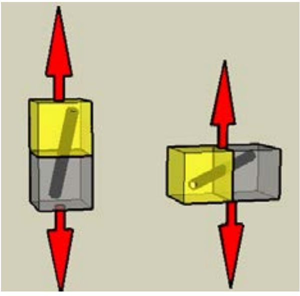

Figure 10: Alignment of lattice elements between differently simulated voxels of repair material and concrete substrate, loaded in direct tension

As a consequence of being aligned more horizontally, these elements need more tensile force for fracture and they start breaking after failure of more vertically aligned ones. Therefore, they reach maximum stress level after peak load in load-strain diagram. That is why in fracture propagation, for the same deformation level, in specimens with simulated rough surface, there is still some force which can be transferred between debonded surfaces. It is transferred through these elements and it is them that make stress-deformation curve more ductile. In practical conditions, in rough interfaces, as a consequence of presence of stiff aggregates at the contact zone and higher interlocking, crack face bridges will be formed. Remaining stress will be transferred through them and it will result in more uniform distribution of repair material and concrete substrate at failure plain. This was observed by [2, 19] after profilometry measurements. Part of the energy that is needed to break the bond, is partly used to break mechanical interlocking and shear friction force between particles.

Contrary, in the smooth surface, there is no mechanical interlocking, no friction between debonded area. The interface elements have higher probability of being aligned more vertically (Figure 10), so less force is needed for breaking them. In addition, all of them break almost immediately which results in fast and brittle failure of the composite system.

4.2 Shear bond test

Specimens in the shear test were loaded by prescribing the horizontal displacement to the left and right edge (Figure 4). In-plane deformations in these nodes were restrained while the rotations were allowed. Crack initiation started from the sides. The stress displacement curves for rough and smooth type of surface preparation versus crack mouth sliding displacement (CMSD) are plotted in Figure 11.

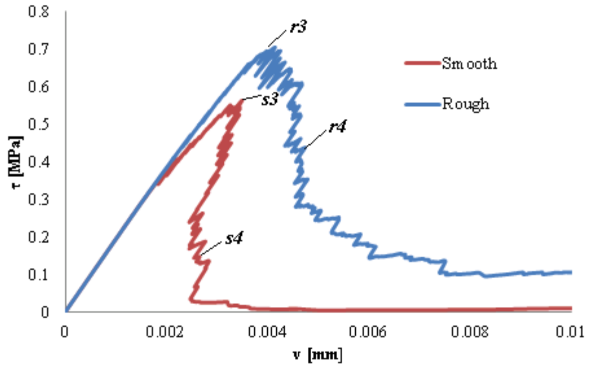

Figure 11: Shear stresses plotted against horizontal (sliding) displacement.

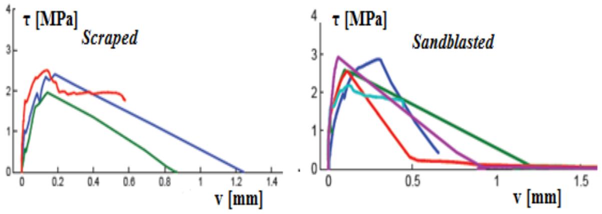

Figure 12: Experimental results for shear bond test [18]

If compared to experimental results (Figure 12) [18], simulated curves are too brittle. This is because, in the shear test, compressive force starts to become dominant, and compressive failure is more difficult to simulate in the lattice model.

Failure mode and crack propagation in the two specimens is presented in Figure 13 with corresponding points where the snapshots were made (from Figure 11). s1, s2, r1, r2 present smooth and rough specimens, respectively, with the same number of broken elements, before reaching the peak load. As can be seen, although localization of debonding both for the rough and smooth surface starts at the ends, it seems that in the rough surface there is more distributed microcracking ahead of the localized crack. The failure is more stable and the energy to break the sample is much higher than in case of smooth surface. In the smooth surface specimen, there is larger localization of debonded area and faster crack propagation.

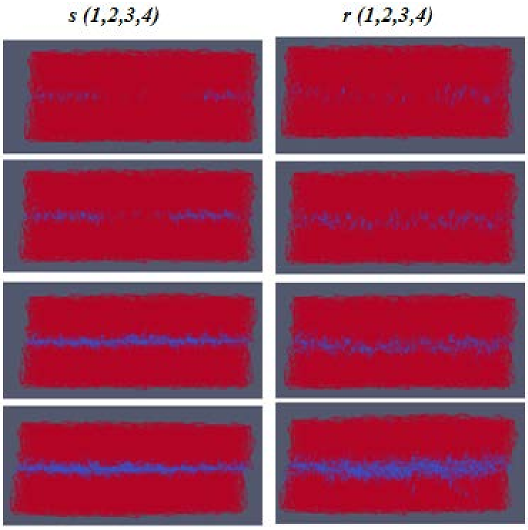

Figure 13: Debonding history of simulated shear test for smooth and rough surface

Considering shear bond strength, it seems that the increased roughness has more influence on the obtained values. Higher roughness provides around 25% higher values for shear bond strength than in case of smooth surface. This correlates well with some experimental results [8, 20]. Shear strength values obtained for each type of simulated surface are shown in Figure 14.

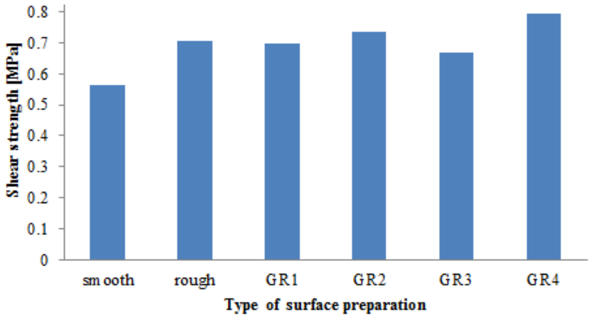

Figure 14: Shear strength for different surface preparation

Interesting to notice here is that shear force increases substantially for the profile GR4. It seems, therefore that bigger grooves with larger spacing and depth (lower frequency than in GR2) are more beneficial for the shear bond strength. They probably enables better mechanical interlocking of two systems and more uniform distribution of shear stresses at the interface. In order to understand this better, stress-strain diagrams for different types of simulated surface roughness are presented in Figure 15.

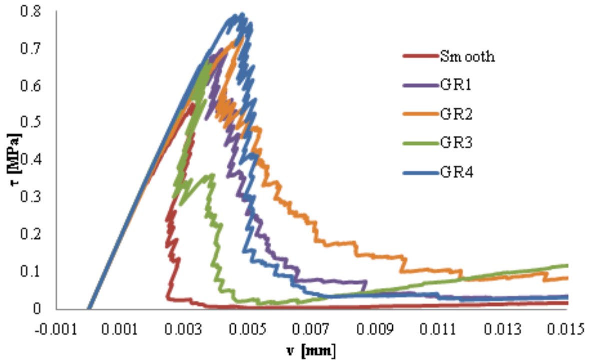

Figure 15: Stress-displacement curve for varied roughness parameters

From the graph it seems that the same amount of energy is needed to break GR2 and GR4, but system with lower frequency of roughness seems to withstand higher peak load.

From the bond strength values obtained by simulated direct tensile and shear test, relation between shear and tensile bond strength is calculated (Figure 16). Obtained shear strength is about twice as big as tensile bond strength. These results match well with data found in literature [3, 11]. Delatte [9] indicated mean ratio of 2 for shear bond vs. tension bond, while Silwerbrand [10] found a ratio between torsional shear bond strength and tensile pull-off strength in range 2 to 3.

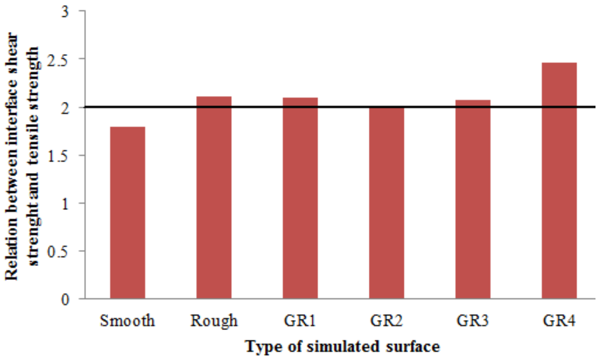

Figure 16: Ratio of shear bond to tensile bond for different simulated surfaces

4.3 Three point bending test

The specimen in three point bending test was loaded by prescribing the vertical displacements in the middle. Displacement of the left and right edge elements in the beam is restrained. Repair material is loaded in tension, with the thickness of 4 mm (Figure 4).

The load-displacement curves for all types of surfaces are plotted in Figure 17. As can be noted, there is almost no difference in response of the system with different simulated roughness. Maximum force for all six specimens was virtually the same (maximum difference 1.4%). That surface roughness of concrete substrate prior to application of repair material has no effect on load-strain curve obtained in bending test, was also observed by [19, 20]. In order to see if there exists a difference in fracture propagation in the systems with various roughness parameters, the steps with same number of broken elements are compared (Figure 18).

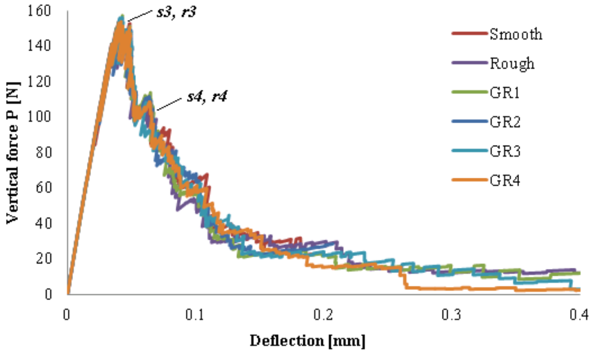

Figure 17: Force-deflection diagram in three point bending for all types of surfaces

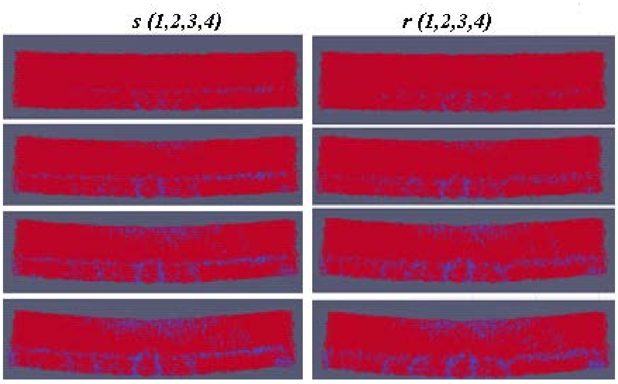

Figure 18: Debonding propagation in specimens with smooth and rough surface

Cracking starts to develop from the zone with highest tensile stresses, at the middle bottom part. Very fast, fracture zone reaches interface zone and debonding starts propagating. At a certain moment, compressed top zone, where the load is applied, starts cracking as well. The difference between smooth and rough surface is, again, in localization of the debonded area. Smooth surface seems to have larger debonding length although both specimens can withstand the same load. This was also observed in [19] where under static loading, measured relation between deflection and load for each type of surface preparation was the same. The crack pattern was similar as one obtained by simulation. But debonding length for surfaces prepared by scarification (relatively smooth) was substantially higher than for surfaces prepared by sandblasting and hydrojetting (rough surface). Therefore, it is observed that roughness does not increase bearing capacity of composite elements, but it enables more monolithic response and reduces probability of debonding.

4.4 Future tests and simulations

In further research, influence of the mesh size dependence on simulated results will be investigated. Also, different properties will be assigned to aggregates, matrix and interface elements in composite system in order to present materials more realistically.

Experiments will be done to investigate influence of surface roughness on the tensile and shear bond strength as well as composite behaviour of the system in bending.

Drying shrinkage is considered to be main reason for premature failure of repairs. The influence of roughness on this phenomena as well, will be investigated. It is expected that rough surface will give more restrain to shrinkage. Therefore, bond between repair material and concrete substrate in rough surfaces may be less damaged than in smooth surfaces. On the other hand, higher stresses will develop in repair material, which may lead to cracking.

5 CONCLUSIONS

Based on above results and discussion, following conclusions can be drawn:

- Roughness has different influence on results obtained in different bond strength tests
- It seems that increased roughness does not affect substantially the bond strength itself (around 6%), but it enables more stable fracture and more ductile performance under uniaxial tension test. Larger fracture energy is needed for failure and failure itself is not so brittle as in case of smooth surface.
- Higher roughness leads to increase in shear bond strength (by 25% compared to the smooth surfaces bond).
- Ratio of 2 between shear bond strength and tensile strength is obtained from simulated tests
- Roughness does not have influence on stress-strain diagram in bending but has influence on debonding length and enhances monolithic behaviour of the system

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