

Investigations on fracture in reinforced concrete beams in 3-point bending using continuous micro-CT scanning

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Abstract

This study explores a fracture process in rectangular reinforced concrete (RC) beams subjected to quasi-static three-point bending. RC beams were short and long with included longitudinal reinforcement in the form of a steel or basalt bar. The ratio of the shear span to the effective depth was 1.5 and 0.75. The focus was on the load-deflection diagram and crack formation. Three-dimensional (3D) analyses of the size and distribution of pores and cracks were carried out with an X-ray micro-computed tomography system SkyScan 1173 of high resolution that is a very valuable non-destructive tool for studying a 3D material interior. The tomography system was connected with a quasi-static loading machine ISTRON 5569 to continuously follow fracture changes without loading breaks. The beams failed in shear due to a diagonal shear crack that was steeper with basalt reinforcement. The shear strength and flexural strength of RC beams with steel reinforcement were higher by about 10% than of RC beams with basalt reinforcement. The deflection corresponding to the maximum load of RC beams was higher by about 20-25% in RC beams with basalt reinforcement due to its lower basalt modulus of elasticity. The final volume of cracks in beams reinforced with basalt bars was higher by about 9-20% than in concrete beams reinforced with steel bars due to a higher beam deflection whereas the maximum crack width in concrete beams reinforced with basalt bars was higher by about 20-40% than in concrete beams reinforced with steel bars. The critical shear crack in RC beams with basalt reinforcement was wider by about 20-40% and steeper by about 10-45% as compared to concrete beams with steel reinforcement. The relationship between the crack volume and beam deflection was bi-linear. Both, aggregate breakage and crack branching occurred during beam bending.

Keywords: X-ray micro-CT; continuous scanning; reinforced concrete; 3-point bending; shear failure; fracture

1. Introduction

Concrete is a dominant composite building material in the world in terms of volume that is widely used in the field of civil engineering due to easy fabrication and the lowest ratio between cost and strength as compared to other available materials. It possesses high compressive strength but both low tensile strength and ductility. Thus, it is vulnerable to cracks under static and dynamic loading which are a fundamental phenomenon in concrete materials [1]-[4]. At the mesoscopic level, concrete is a typical composite material consisting of multi-phases, including coarse and fine mineral aggregates, cement matrix, voids and interfacial transition zones (ITZs) between the aggregate and cement matrix. The diameter of coarse aggregate ranges from millimetres to centimetres whereas ITZs are only several dozen micrometres and the hydrated cement is few nanometres in width. Coarse aggregates with irregular shapes are randomly embedded in the mortar. Porous ITZs around aggregates are significantly weaker than aggregate and mortar and become attractors for a micro-crack propagation along aggregate boundaries. As a consequence, the concrete structures are strongly heterogeneous, demonstrating a non-linear stress-strain behaviour [5]-[7]. The assessment of the structural optimization and safety for quasi-brittle materials (like concrete) requires, however, a comprehensive understanding of the micro- and macro-cracking formation and propagation. Therefore, it is necessary to investigate a 3D meso-scale damage formation for evaluating the failure extent of materials.

Different experimental techniques have already been used to investigate a fracture process in quasi-brittle materials like concrete. Among the variety of techniques, the most popular are the scanning electron microscopy [8], [9], laser-spot [10], interferometry [11], [12], acoustic emission [13]-[15], neutron imaging [16] and X-ray micro-computed tomography (micro-CT) [17]-[32]. The use of X-ray micro-CT recently gained the highest popularity in reproducing and a better understanding of real 3D meso-structure of different cementitious materials. X-ray micro-CT enables to visualize and analyze quantitatively a shape and distribution of macro-pores, aggregate particles, fibres and cracks. Micro-CT may determine the 3D meso-structure inside the concrete material without destruction since different composition phases correspond to different X-ray absorption coefficients. Micro-CT images are collections of 2D grayscale images (the so-called slices) that are stacked digitally for revealing the entire 3D internal specimen structure. The smallest element of this 3D image is a voxel which possesses a grayscale value corresponding to the material density. The shortcomings of micro-CT concern both resolution and solid-phase separation capability. Our tomography system SkyScan 1173 has already been successfully used for observations of the

68 evolution of a concrete fracture process during three-point bending in plain concrete [18], [19], [29],
69 tension splitting in plain concrete [21], uniaxial compression in plain concrete [22], compressive
70 fatigue in plain concrete [23], It was also used in fibrous concrete with steel and basalt fibres [30]-
71 [32]. The potential of micro-CT in concrete fracture propagation research was clearly demonstrated.
72 The micro-CT images became an extremely valuable tool for constructing and validating numerical
73 mesoscopic 2D and 3D models for concretes within continuum mechanics [33]-[39] and discrete
74 mechanics [40]-[42]. Based on micro-CT images, we formulated a very realistic discrete element
75 model for quantitative describing a fracture process in concrete under different loading types [18],
76 [21], [22], [40]-[42].

77

78 The presented research work is experimentally oriented; it concerns reinforced concrete (RC) beams
79 subjected to 3-point bending failing in shear. A combined high-resolution X-ray micro-computed
80 tomography coupled with the quasi-static loading machine ISTRON 5569 was used for shorter
81 beams. Such a system allowed us to capture 3D images of material meso-structure and fracture
82 without the necessity to remove the load during scanning [29]. Thus, a crack closure due to
83 unloading was avoided [29]. The images provided valuable information regarding the real
84 distribution, shape, width and volume of macro-pores and cracks in RC beams. The micro-CT
85 scanning started with an initial scan of non-cracked concrete beams and continued with scans made
86 at 3 different loading points. For comparison purposes, the experiments were also performed with
87 longer beams and two different types of reinforcement (steel or basalt reinforcement) to investigate
88 the effect of both the beam size and reinforcement stiffness on the strength and fracture pattern of
89 beams. The basalt reinforcement is made of volcanic rock basalt. It has some excellent properties
90 such as high corrosion resistance, high tensile strength and low weight. It is resistant against alkali,
91 acids, radiation and UV light, electromagnetic, electric and electrostatic indifference. It possesses
92 high heat stability, environmental friendliness, non-toxicity, low water absorption and the same
93 thermal expansion coefficient as concrete. The disadvantages of this reinforcement are the low
94 elastic modulus, lack of yielding before rupture and low resistance to fire and shear. The
95 compressive strength is lower by 20-50% than the tensile strength and static fatigue may occur. In
96 addition, basalt bars are more expensive than traditional steel bars (ca. 4-5 times).

97

8 The current experimental study includes three novel elements: 1) detailed investigations of a
9 complex 3D fracture process at the aggregate level in RC beams of different size and reinforcement
0 type under quasi-static 3-point bending using micro-CT, 2) continuous scanning of a 3D fracture
1 process in reinforced concrete beams under 3-point bending without their unloading and 3)
2 determination of a relationship between the crack volume and beam deflection. The volume of pores



103 and cracks was determined in numbers for four different beam deflections. All beams did not
104 include vertical shear reinforcement and hence failed in shear. Experimental results were compared
105 with our other similar experimental outcomes on large RC beams using steel [43], [44] and basalt
106 longitudinal reinforcement [43], [45] that also failed in shear. The micro-CT results in this paper
107 may thus be used as a benchmark for numerical models to describe fractures in RC beams (e.g. [18],
108 [21], [38], [40]). The micro-CT system has not been used for studying a fracture process in RC
109 elements under mechanical loading yet in contrast to plain [46] and fibrous [31] concretes.

110

111 **2. Experimental program for micro-CT**

112 **2.1 RC beam preparation**

113

114 Concrete blocks were prepared from a mix including round-shaped aggregate particles with the
115 mean diameter of $d_{50}=2$ mm and the maximum diameter of $d_{max}=16$ mm (Figure 1) with the addition
116 of cement CEM I 32.5R and water. The water/cement ratio was $w/c=0.42$. A small amount of
117 superplasticizer was added to improve the workability of the fresh concrete. The concrete mix
118 components are presented in Table 1. Two cubic concrete blocks with the dimensions of
119 $300\times 300\times 100$ mm³ reinforced with one steel or basalt bar of the diameter 6 mm were prepared. The
120 basalt fiber content was 80% and the epoxy resin was 20%. The reinforcement ratio was always
121 $\rho=1.8\%$. The height of the ribs was 0.85 mm (steel bars) and 0.65 mm (basalt bars). The mechanical
122 properties of reinforcement were as follows: the tensile strength of basalt $f_{yb}=1100$ MPa and steel
123 $f_{ys}=650$ MPa and the modulus of elasticity of basalt $E_b=70$ GPa and steel $E_s=200$ GPa. For the first 7
124 days, the blocks were properly cured to eliminate the negative effect of autogenous shrinkage on
125 planned test results [47]. Afterward, long (Figure 2) and short (Figure 3) rectangular reinforced
126 concrete beams were cut out on the 28th day. All beams had the same cross-sectional dimensions,
127 i.e. height $h=40$ mm and width $b=40$ mm. The effective height was $D=30$ mm (the concrete cover
128 was 7 mm). The long beams had a length of $L=160$ mm and span of $L_s=120$ mm ($L_s/D=3$) and the
129 ratio of a shear span and effective depth $a/D=1.5$. The short ones had a twice smaller length ($L=80$
130 mm), span ($L_s=60$ mm, $L_s/D=1.5$) and shear span ratio $a/D=0.75$. The dimensions of short beams
131 were selected to be entirely visible in the field-of-view of our micro-CT system. The short beams
2 were continuously scanned using the micro-CT equipment mounted on the Instron 5569 loading
3 machine whereas the long beams were designated for scanning after the tests only. The average
4 uniaxial compressive strength of concrete [48] was $f_c=49.75$ MPa with the standard deviation of
5 2.14 MPa (tested on 3 cubic concrete specimens $15\times 15\times 15$ cm³), the average Young's modulus [49]
6 $E=34.8$ GPa with the standard deviation of 2.04 GPa and the average Poisson's ratio $\nu=0.21$ with

137 the standard deviation of 0.02 (tested on 3 cylinder concrete specimens $15 \times 30 \text{ cm}^2$). The mean
138 tensile strength during bending was $f_t = 3.96 \text{ MPa}$ [50] with the standard deviation of 0.22 MPa
139 (tested on 3 concrete beams $60 \times 15 \times 15 \text{ mm}^3$). Due to a high value of $\rho = 1.8\%$, small ratio $a/D = 0.75$ -
140 $1.5 < 3$ and lack of vertical reinforcement, a diagonal critical shear crack was expected to appear at
141 the failure [43]-[45]. The laboratory tests were carried out with a displacement controlled option
142 using the rate of 0.05 mm/min (long beams) and 0.002 mm/min (short beams).

143

144 **2.2 X-ray micro-CT scanning**

145

146 Since the beams of Figure 2 were too long to be inserted in an axial field-of-view, the usual
147 scanning technique was used, i.e. the beams were scanned in a vertical position after a bending test
148 was ended. The SkyScan 1173 scanner (Figure 4) was directly used for this usual scanning. The
149 voltage and current were 130 keV and 61 μA . The scanning resolution resulted in a voxel size of
150 39 microns. The exposure time was settled on 5000 ms and the 0.2 mm brass filter was used. The
151 beam was scanned at 360° with a single rotation step of 0.6° . The beams were scanned in two sub-
152 scans by moving a rotation table down after the first sub-scan was completed. The reconstruction
153 was made sub-scan by sub-scan with the necessary adjustment in file sequences to form a complete
154 stack of the 3D volume.

155

156 For continuous scanning of short reinforced concrete beams of Figure 3, the SkyScan 1173 scanner
157 was this time connected with the static Instron 5569 machine (Figure 5). To rotate loaded beams,
158 a rotating table and stepper motor, controlled from the micro-CT software, were designed
159 (Figure 5). The scanning process lasted 45 minutes. The voxel size was 46 microns and the
160 exposure time was 3000 ms. The beam was scanned at 180° with a single rotation step of 0.6° .

161

162 The image reconstruction was carried out with the commercial software NRECON, CTAn and
163 CTVox (Bruker microCT, Belgium). To reduce ring artifacts in reconstructed cross-sections, a
164 random movement with the amplitude of 4 (number of camera lines) was used. To improve the
165 image quality, the averaging option was set on 2 (number of frames). It averaged several images in
166 each angular position. To distinguish pores, cracks and reinforcement from concrete on images, a
7 careful threshold procedure based on density differences was performed (that is crucial for
8 obtaining the material meso-structure from micro-CT scans). In our experiments, pores and cracks
9 were separated from concrete with the threshold value in the range 0-70 whereas steel
0 reinforcement with the threshold 230-255. The first threshold range value was validated, based on
1 comparative measurement results of the air content in the concrete mass using the air pressure

172 method and porosity in concrete beams using micro-CT. The air content was 2.70%, 2.90% and
173 3.0% with an average value of 2.87% and the porosity was 2.64%, 3.04%, 2.67% and 2.83% with
174 an average value of 2.79%. Both the average values were similar (which confirmed the threshold
175 range value assumed in experiments). The basalt reinforcement could not be clearly distinguished
176 from concrete due to the same density as the mortar. The pores were treated in two ways, i.e. as
177 open pores that crossed the boundaries of VOI (volume of interest) or as closed pores that were
178 entirely embedded in VOI. The volumes of pores (open, closed and total) and cracks were
179 automatically measured. To calculate the actual crack volume, the volume of initial pores was
180 subtracted from the actual volume of total pores.

181

182 **3. Experimental micro-CT results for long RC beams**

183

184 Figure 6 and Table 2 show the initial 3D content and distribution of-pores in non-cracked steel and
185 basalt reinforced concrete beams measured by micro-CT. The initial volume of macro-voids in a
186 non-cracked long concrete beam with a steel bar was 2.64% of the total beam volume (2.14% -
187 closed pores and 0.50% - open pores) and with a basalt bar was 3.04% of the total beam volume
188 (2.42% - closed pores and 0.62% - open pores). Thus, the total initial porosity of concrete beams
189 with steel reinforcement was smaller by about 15% than the porosity of concrete beams with basalt
190 reinforcement. Figure 6Ab shows that between steel bar ribs some free space was left. The free
191 space was not observed between basalt bar ribs (Figure 6Bb).

192

193 Figure 7 presents the evolution of the vertical force F versus the deflection u for long concrete
194 beams with a single steel and basalt bar subjected to three-point bending. The evolution of both
195 curves was similar. The maximum vertical force of concrete beams with a steel bar was 4.77 kN
196 and was higher about 10% than with a basalt bar - 4.35 kN. The deflection at the maximum force of
197 the concrete beam with a steel bar, 0.57 mm, was about 25% smaller than with a basalt bar,
0.77 mm, due to the lower modulus of elasticity of basalt. The shear strength, $V=F_{max}/bD$, was
198 3.97 MPa (RC beam with a steel bar) and 3.62 MPa (RC beam with a basalt bar). The flexural
199 strength, $M=1.5F_{max}L_s/bh^2$, was 13.48 MPa (RC beam with a steel bar) and 12.23 MPa (RC beam
200 with a basalt bar). A double force peak occurred during deformation (which is typical in RC beams
1 if the concrete cover is large enough [51]). After reaching both the peak values, the vertical force
2 decreased. The beams' failure was brittle.
3
4

205 The crack development and failure mechanism were similar for concrete beams with two different
206 reinforcement types. First, one (beam with a steel bar) or two flexural cracks (beam with a basalt
207 bar) appeared at the area of the beam mid-span (that caused an initial jump on the force-deflection
208 curve in Figure 7). Later, short inclined (shear) cracks developed in a shear span region that
209 continuously evolved in length and width with increasing deflection. Next, one inclined dominant
210 shear crack started to stronger develop. The failure took place in a rapid brittle way (independently
211 of the reinforcement type) due to a diagonal critical shear crack at one beam side (the co-called
212 shear-compression failure took place that is typical for the small ratios $a/D < 2$ [45]) (Figures 8
213 and 9). The critical shear crack propagated from the bottom at the support region through the entire
214 beam height up to the loading point. It propagated directly from the support at one side only
215 (Figure 9) independently of the reinforcement type. On the other side, it was located at a certain
216 distance from the support. Thus, a strongly non-symmetric shear-compression failure mode took
217 place in beams. In addition, at the failure, a horizontal splitting macro-crack propagated from the
218 critical shear crack along a basalt bar towards its end (Figures 9b and 10b). The bond between the
219 concrete and steel bar was undamaged (Figure 10a). There existed, however, small cracks at each
220 steel bar rib (Figures 8A and 10a). Just before the failure, some secondary cracks on the lateral sides
221 of the beams also happened due to the bond damage (Figure 9). They appeared around the
222 reinforcement bar on the beam lateral side with a steeper shear crack, being at a longer distance
223 from the support (Figure 9). The crack volume in the concrete beam with steel reinforcement was
224 4.11% and basalt reinforcement was 4.52% (higher by 10%) after the test. The maximum crack
225 width measured perpendicularly to the crack axis was 1.39 mm for the deflection $u=1.05$ mm in the
226 RC beam with a steel bar and 1.68 mm ($u=1.03$ mm) with a basalt bar (Table 2). The final critical
227 shear macro-crack was strongly curved and its shape and width varied along with the beam depth
228 and height due to the heterogeneous nature of concrete (mainly due to the presence of aggregate
229 particles different in shape and size) (Figures 8 and 9). The mean inclination of the critical shear
230 crack to the bottom was 31° (beam front) and 60° (beam rear) for a steel bar and 43° (front and rear
231 side) for a basalt bar (Figure 8). The cracks mainly propagated through the cement matrix and ITZs
232 around aggregates which were the weakest phase in concrete (Figure 11). Occasionally, the crack
233 propagated through single weak aggregate particles (Figure 11). The crack branching also occurred
234 during quasi-static bending (Figure 11). The greater the maximum crack width (connected with the
5 higher crack volume) in the RC beam with basalt reinforcement was caused by a lower modulus of
6 elasticity of basalt [33], [34].
7

8 **4. Experimental micro-CT results for short RC beams**

239

240 Figure 12 and Table 3 show the initial 3D content and distribution of pores in short non-cracked
241 steel and basalt RC beams ($L=80$ mm) measured by micro-CT.

242

243 The initial volume of pores in a non-cracked short concrete beam with a steel bar was 2.67% of the
244 total beam volume (the closed and open pores were 2.04% and 0.63%, respectively) and with a
245 basalt bar was 2.83% of the total beam volume (the closed and open pores were 2.24% and 0.59%,
246 respectively). The volume was again higher in the beam with a basalt bar (by about 5%).

247

248 The maximum vertical force of concrete with a steel bar 10.46 kN was about 15% higher than this
249 with a basalt bar 9.05 kN (Figure 13). The shear strength for short beams, $V=F/bD$, was 8.72 MPa
250 (steel bar) and 7.54 MPa (basalt bar) and for long beams 3.97 MPa (steel bar) and 3.62 MPa (basalt
251 bar). Thus, it increased with decreasing a/D and L/D [45]. The flexural strength was 14.71 MPa
252 (RC beam with a steel bar) and 12.73 MPa (RC beam with a basalt bar). It was higher by 5-
253 10% than in long RC beams. The force-deflection diagram for short beams was slightly different
254 than for long beams since a clear jump did not occur in the pre-peak region, softening after the peak
255 load was more pronounced (in particular in the beam with a steel bar) and small re-hardening
256 occurred in the beams after the peak load. The beams' failure was again brittle. The deflection
257 corresponding to the maximum force was again higher (by about 20%) in the RC concrete with a
258 basalt bar (0.33 mm) than in the RC beam with a steel bar (0.26 mm).

259

260 The RC beams were three times scanned by micro-CT for the different beam deflections: 1) close to
261 the peak load (point '1' in Figure 13), 2) after the peak load in a softening regime (point '2' in
262 Figure 13) and 3) close to the failure (point '3' in Figure 13). Figures 14a and 15a show the initial
263 external view on the beam and the 3D distribution of pores from 2 different views. Figures 14b-d
264 and 15b-d present images for the various loading points from 2 different views. The volume of
265 pores in the non-cracked beams before the test was 2.67% and 2.83% for the RC beam with a steel
266 and basalt bar, respectively (Table 3). At point "1" of Figure 13, the flexural cracks appeared in the
267 beam span (Figures 14a and 15a) and the volume of pores and cracks increased by about 7.5%
268 (beam with a steel bar) and by about 17% (beam with a basalt bar). The largest crack width for the
9 concrete beam with a steel bar was $w_{cs}=0.16$ mm and with a basalt bar was $w_{cb}=0.27$ mm (higher by
0 60%). At point "2" of Figure 13, the first inclined (shear cracks) were observed (Figures 14b and
1 15b) and the volume of pores and cracks grew as compared to the point '1' by about 50% (beam
2 with a steel bar) and by about 45% (beam with a basalt bar). The largest crack width in the concrete
3 beam with a steel bar was $w_{cs}=0.48$ mm and in the concrete beam with a basalt bar was

274 $w_{cb}=0.72$ mm (higher by 35%). For point “3” of Figure 13, the inclined shear cracks evolved in
275 length and width (Figures 14c and 15c) and the volume of pores and cracks increased as compared
276 to the point ‘2’ by about 40% for both the beams. The largest crack width in the RC beam with a
277 steel bar was $w_{cs}=1.25$ mm and with a basalt bar was $w_{cb}=1.78$ mm (higher by 40%). Finally, the
278 beam failure took place in a rapid brittle way in both RC beams due to a diagonal shear crack
279 moving from the support region through a beam compressive zone towards the loading point. The
280 critical shear crack in the RC beam with a steel bar propagated from the support to the loading point
281 as the outermost crack (Figure 16) and in the beam with a basalt bar was situated closer to the mid-
282 span of the beam at one side (front side). Similarly, as in long beams, some secondary cracks were
283 visible on the lateral end sides of beams just before the beam failure. For a basalt bar (Figure 17b),
284 the contact between concrete and a bar was again damaged at the failure - a horizontal splitting
285 macro-crack propagated also along a basalt bar towards its end (similarly as in a long RC beam).

286
287 The mean inclination of the critical shear crack to the bottom was 59° (front side) and 57° (rear side)
288 for the RC beam with a steel bar and 75° (front side) and 50° (rear side) for the RC beam with
289 a basalt bar. The critical shear macro-cracks were steeper than in long beams due to a smaller ratio
290 a/D . As compared to long RC beams, the final maximum width of cracks was smaller (by 10%) in
291 the RC beam with a steel bar and larger (by 8%) in the RC beam with a basalt bar. The final crack
292 volume was lower in short beams than in long beams by 25% (beams with steel reinforcement) and
293 by 15% (beams with basalt reinforcement).

294
295 The change of the crack volume during bending is presented in Tables 4 and 5 and Figure 18. For
296 comparison purposes, the final results shown in Figure 18 are also presented for long RC beams.
297 A relationship between the crack volume and beam deflection (based on four micro-CT
298 measurements) was bi-linear for both reinforcement types in short RC beams (Figures 18a and 18b).
299 The final crack volume was about 3.3%-4.0% in short beams. It was slightly lower than in long RC
300 beams (4.1%-4.5%, Figures 18c and 18d). The change of the curve inclination occurred at the peak
301 load region where the crack volume was about 0.2-0.5%. For the deflection of $u=1.0$ mm, the crack
302 volume was slightly lower in long beams assuming a continuous linear development of the crack
303 volume in short beams between $u=0.75-0.80$ mm and $u=1.0$ mm.

4
5 The vertical cross-sectional micro-CT images in the beams (successively at 5 mm from the beam
6 front side, at the beam mid-width and at 5 mm from the beam back side) of short concrete
7 reinforced beams with steel or basalt reinforcement for the point ‘3’ of Figure 13 are demonstrated
8 in Figures 19 and 20. The crack width was measured perpendicularly to the crack axis and the

309 inclination angle was measured in relation to the horizontal line. The manual measurements were
310 carried out in nine points. The shear crack width in the tensile region of the concrete beam
311 reinforced with steel bar non-linearly changed with the beam height from $w_{cs}=0.19$ mm down to
312 $w_{cs}=1.25$ mm (the average value was 0.61 mm with the standard deviation of 0.43 mm), whereas the
313 inclination angle varied between $\alpha_s=26^\circ$ and $\alpha_s=87^\circ$ (the average value was 49° with the standard
314 deviation of 25°). The shear crack width in the tensile region of the concrete beam reinforced with a
315 basalt bar non-linearly changed with the beam height from $w_{cb}=0.25$ mm up to $w_{cb}=1.78$ mm (the
316 average value was 1.08 mm with the standard deviation of 0.48 mm) whereas, the inclination angle
317 varied between $\alpha_b=10^\circ$ and $\alpha_b=96^\circ$ (the average value was 54° with the standard deviation about
318 29°). It can be concluded (by taking into account the average values) that the critical shear crack in
319 the concrete beam with basalt reinforcement was wider by about 75% as compared to the critical
320 shear crack in the concrete beam with a steel bar. It was also steeper by about 10% on average. The
321 crack propagated again sometimes through single weak aggregate particles. The crack branching
322 also occurred.

323

324 The results in Sections 3 and 4 were shortly compared with our earlier experiments on large RC
325 beams without vertical reinforcement during three- and four-point-bending) with steel
326 reinforcement ($h=200-800$ mm, $L=1500-6000$ mm, $a/D=1$, $\rho=1\%$ [43], and $h=200-400$ mm,
327 $L=1500-3200$ mm, $a=480-2250$ mm, $a/D=1-3$, $\rho=1.4\%$ [45]) and with basalt reinforcement ($h=220-
328 780$ mm, $L=400-1600$ mm, $a/D=3$, $\rho=0.63\%$ [43], and $h=200-1000$ mm, $L=1600-6000$ mm, $a/D=3$,
329 $\rho=0.85\%$ [44]). The strut-and-tie models following ACI [52] and Zhang and Tan [53] overestimated
330 the shear strength of RC beams with steel reinforcement for $a/h=1.5-2$ (by 20%–100%) and
331 underestimated for $a/h=1$ (by 5%–25%) [45]. The beams' behaviour with steel reinforcement was
332 realistically described using a coupled elasto-plastic-damage model with non-local softening [54].

333

334 As compared to experiments on large beams with steel and basalt reinforcement, the crack
335 development process and failure mode (shear-compression) were similar in the current study. The
336 number of flexural and shear cracks was obviously significantly higher in large beams [43]-[45].
337 The beam deflections and the crack widths were also much higher when basalt reinforcement was
338 used [43]. The bond damage occurred also in large RC beams with steel bars [43], [45]. The shear
339 strength V in large RC beams was also higher with steel reinforcement than with basalt one [44].
340 For the same ratio $a/D=1.5$, the shear strength of large beams with steel reinforcement was $V=2.86$
341 MPa [45] and was thus lower by 40% than the shear strength of RC beams in Section 3 ($V=3.97$
342 MPa) due to a size effect caused by fracture [43].

343

344 The micro-CT experimental results constitute a reliable validation basis of numerical calculation
345 outcomes with different mesoscopic continuous and discontinuous fracture models for concrete.
346 They also provided some practical findings with respect to the 3D non-uniform cracks' shape due to
347 the concrete heterogeneity, presence of voids along steel bar ribs in spite of careful concrete mixing,
348 development of micro-cracks along steel bar ribs, the formation of secondary cracks in beams,
349 propagation of a quasi-static macro-crack through weak aggregates in spite of low loads, crack
350 branching during a quasi-static deformation process and quantitative evolution of the crack volume
351 with concrete deformation.

352

353 **5. Conclusions**

354

355 In this study, experimental investigations of long and short RC beams with a steel or basalt bar
356 under 3-point bending combined with a quantitative description of a fracture process using
357 a continuous/discontinuous X-ray micro-computed tomography system (micro-CT) with high
358 resolution were performed. The following findings can be offered:

359

360 - The shear strength and flexural strength of RC beams with steel reinforcement were higher by
361 about 10% than those of RC beams with basalt reinforcement. The shear strength increased with
362 decreasing ratios a/D and L/D . The shear strength of short RC beams was higher by 2.1-2.2 times
363 than of long RC beams. The normalized shear strength normalized by the beam height was higher
364 by 20% for short RC beams with a steel bar and by 10% for short RC beams with a basalt bar than
365 for long beams. The deflection corresponding to the maximum load of RC beams was higher by
366 about 20-25% in RC beams with basalt reinforcement due to its lower modulus of elasticity.

367

368 - The initial total porosity of non-cracked concrete beams reinforced with a steel bar (2.64-2.67%)
369 was smaller by about 5-15% than of non-cracked concrete beams reinforced with a basalt bar (2.83-
370 3.04%). Micro-CT images scanned before tests revealed the presence of voids along steel bar ribs in
371 contrast to basalt bars.

2

3 - The beam bearing capacity was exhausted in a rapid brittle way through a diagonal critical shear
4 crack that propagated from the bottom through the entire beam height up to the loading point (the
5 so-called shear-compression failure occurred) connected with a horizontal splitting crack along a
6 bar's end in RC beams with a basalt bar. Besides flexural and shear cracks, some secondary cracks

377 on beam lateral sides were created just before the failure due to bond damage. Short cracks also
378 occurred at the ribs of steel bars.

379

380 - The final volume of cracks in beams reinforced with basalt bars was higher by about 9-20% than
381 in concrete beams reinforced with steel bars due to a higher beam deflection. At the same time, the
382 maximum crack width in concrete beams reinforced with basalt bars was higher by about 20-40%
383 than in concrete beams reinforced with steel bars.

384

385 - The critical shear crack in short RC beams with basalt reinforcement was wider by about 40% and
386 steeper by about 20% on average as compared to short concrete beams with steel reinforcement. For
387 long RC beams, the critical shear crack was wider by about 20% when using basalt reinforcement
388 (its mean inclination was similar). The inclination of the critical shear crack at both beam sides
389 could strongly differ. The critical shear crack propagated from the support up to a loading point at
390 one side only. It was the outermost crack in short beams with a steel bar while it was situated closer
391 to the support than the outermost shear crack in short beams with a basalt bar.

392

393 - The final macro-crack was strongly curved and its shape and width varied along with the beam
394 depth and height. The cracks mainly propagated through the cement matrix and ITZs. Sometimes,
395 cracks moved through single weak aggregate particles. A crack branching phenomenon also
396 occurred. The relationship between the crack volume and beam deflection was bi-linear (based on 4
397 scans for the different beam deflection). The final crack volume was 3.27-3.98% in short beams and
398 4.11-4.52% in long beams.

399

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556

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559

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599 are in red, steel bar is in green)

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609 with steel bar ($L=160$ mm) and d) long beam with basalt bar ($L=160$ mm)

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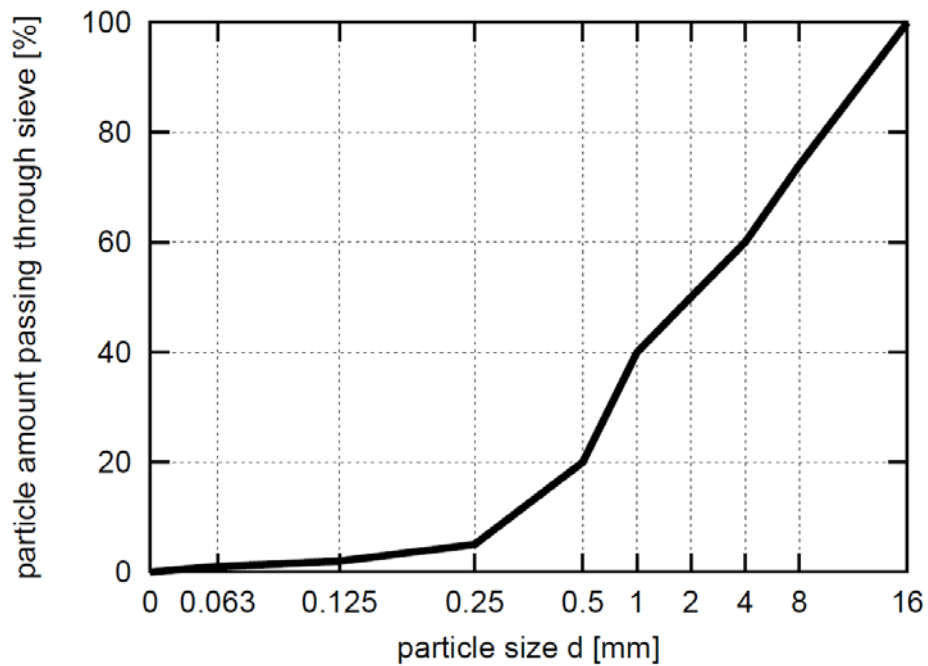
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2 5 mm from front side, b) at beam mid-width and c) at 5 mm from rear side and corresponding
3 measurement results of critical shear crack: d) crack width and e) crack inclination angle

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615 **Figure 20:** Vertical cross-sections of short RC beam ($L=80$ mm) with basalt reinforcement: a) at
616 5 mm from front side, b) at mid-width and c) at 5 mm from rear side and corresponding
617 measurement results of critical shear crack: e) crack width and f) crack inclination angle
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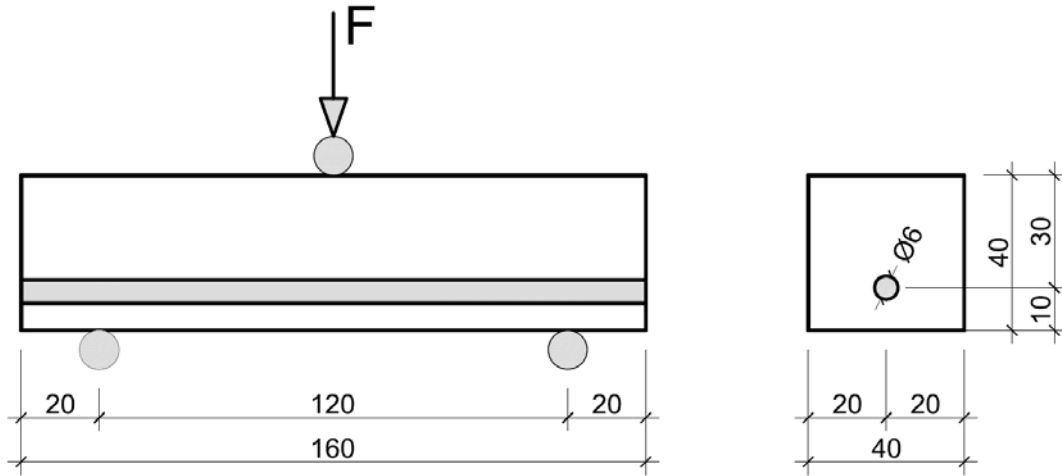


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Figure 1: Particle size distribution curve of concrete (mean particle diameter $d_{50}=2$ mm and maximum particle diameter $d_{max}=16$ mm, d - particle diameter)

FIGURE 1

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647 **Figure 2:** Geometry of long concrete beam reinforced with one steel/basalt bar (dimensions are
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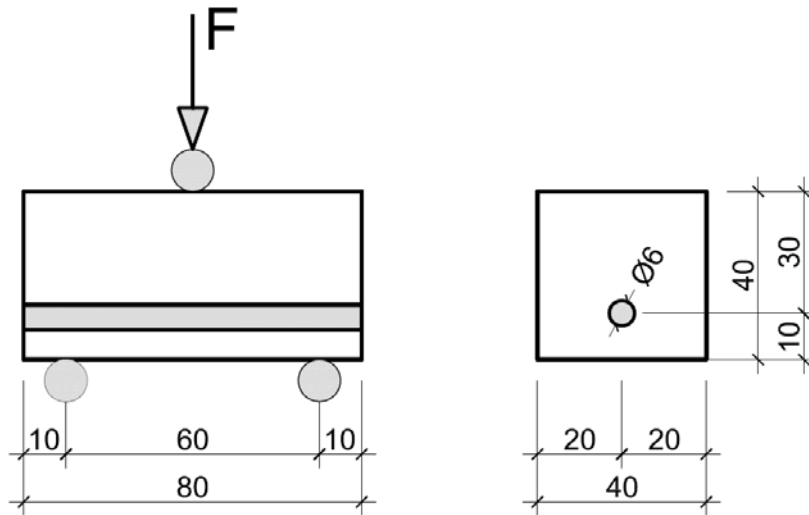
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FIGURE 2

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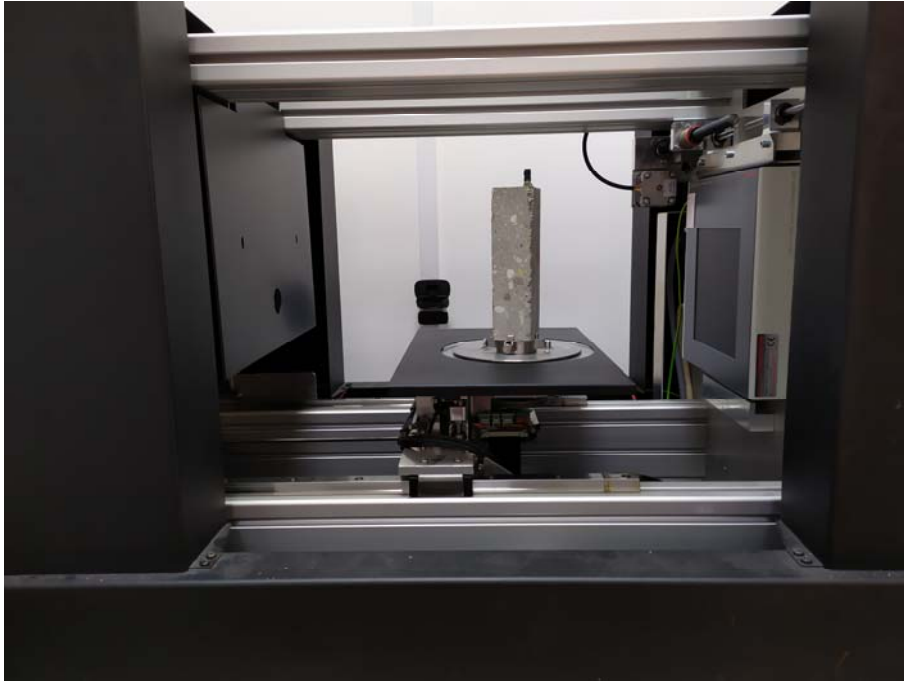
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Figure 3: Geometry of short concrete beam reinforced with one steel/basalt bar (dimensions are in [mm])

FIGURE 3

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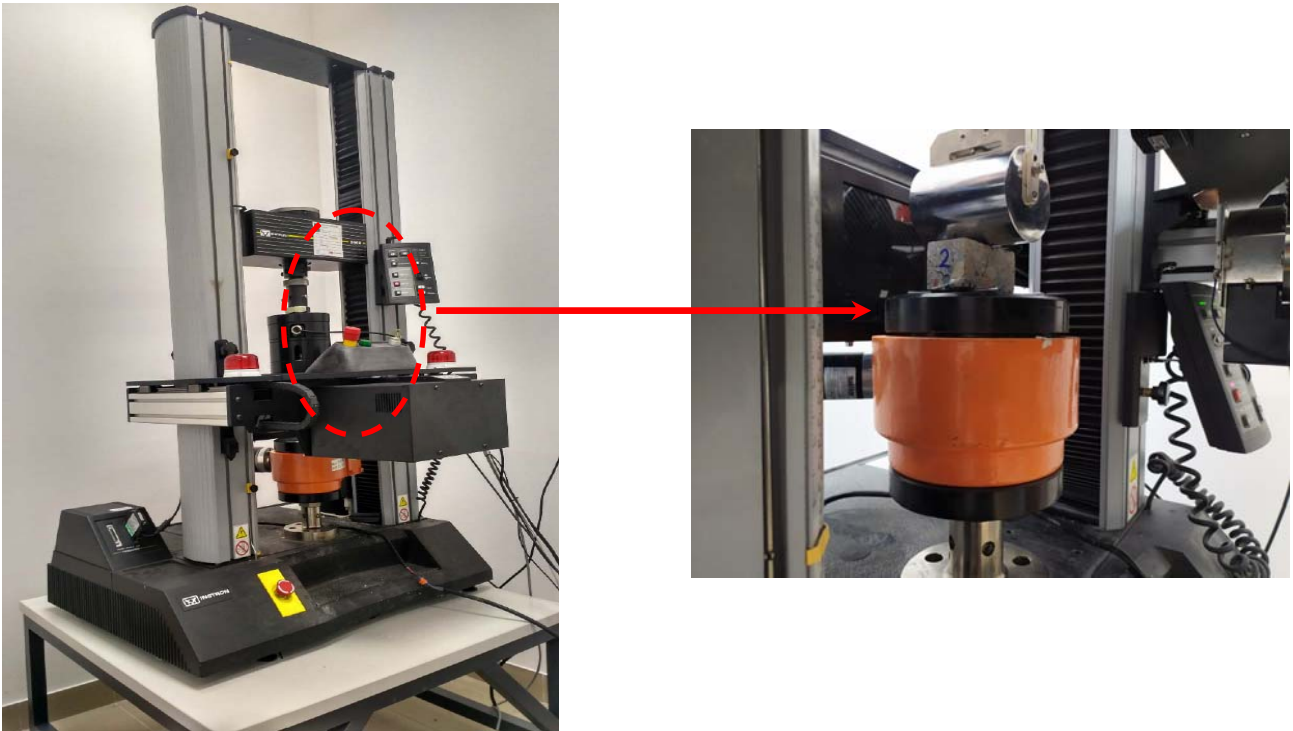


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681 **Figure 4:** Long reinforced concrete beam mounted vertically on rotation table of extended X-ray
682 micro-CT SkyScan 1173 scanner

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FIGURE 4

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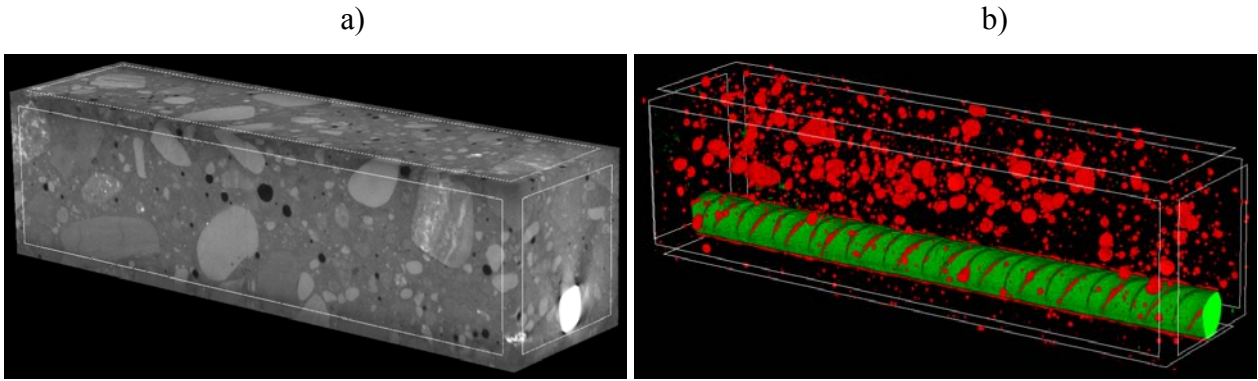


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Figure 5: General view on X-ray micro-CT system Skyscan 1173 mounted on loading machine Instron 5569 and zoom on short reinforced concrete beam mounted on rotation table in horizontal position

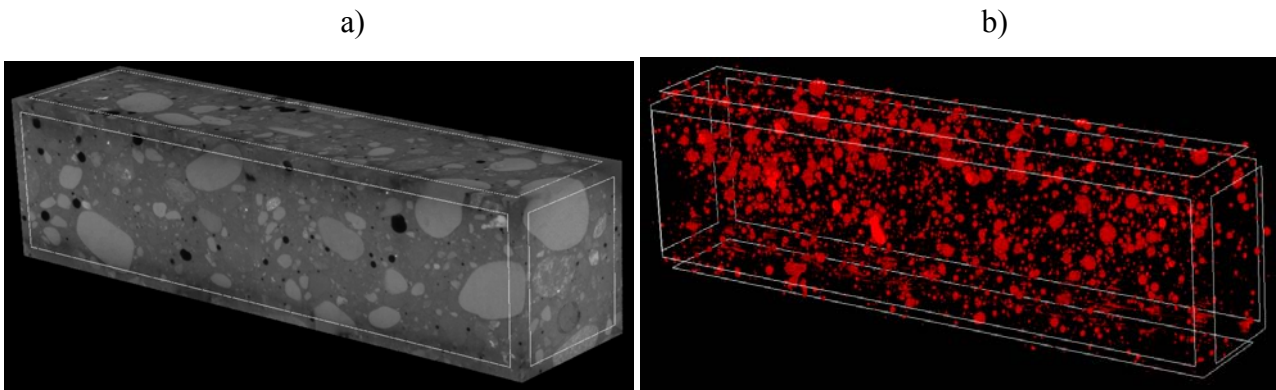
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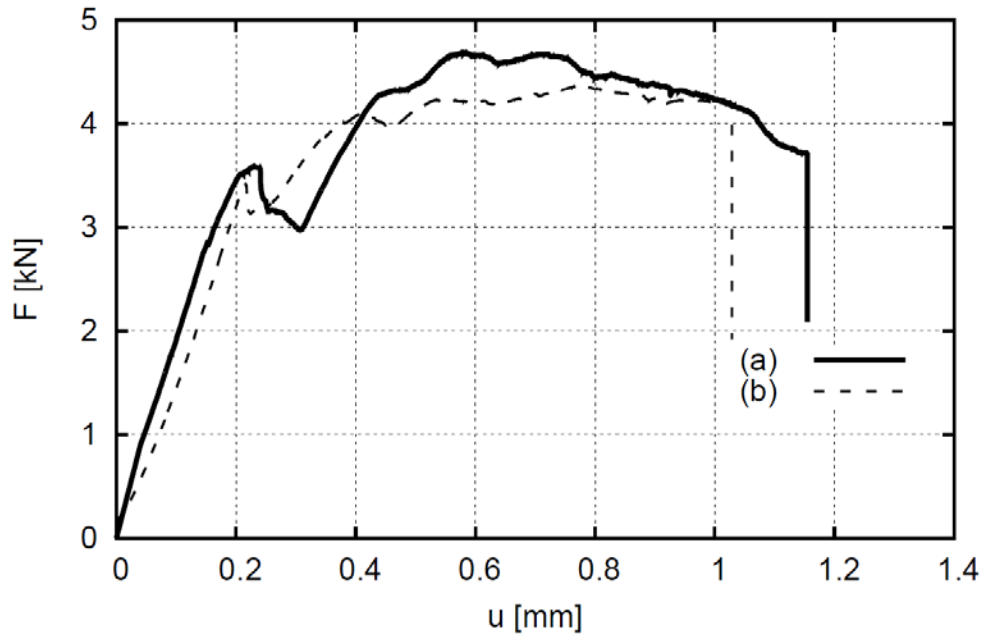
Figure 6: Initial view on beams a) and distribution of pores in 3D micro-CT images b) of non-cracked long RC beams ($L=160$ mm) before loading: A) with steel bar and B) with basal bar

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FIGURE 6

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740 **Figure 7:** Experimental vertical force F - deflection u diagrams for long RC beams ($L=160$ mm)
741 with: a) steel and b) basalt bar

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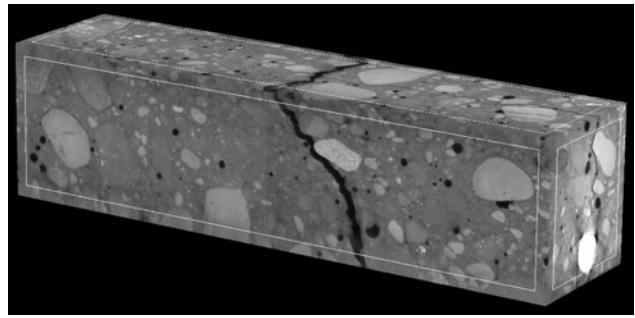
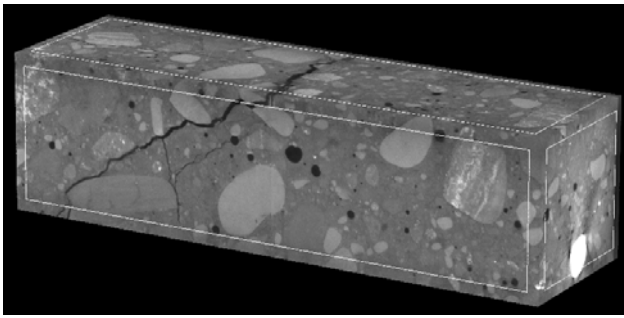
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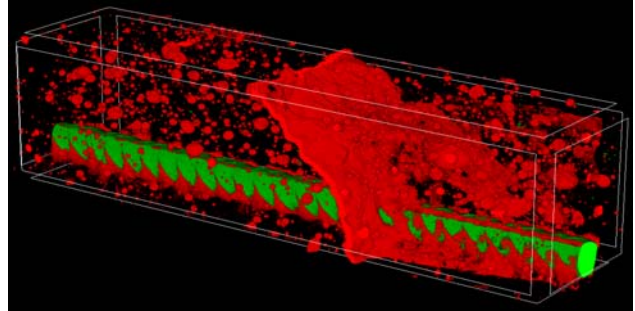
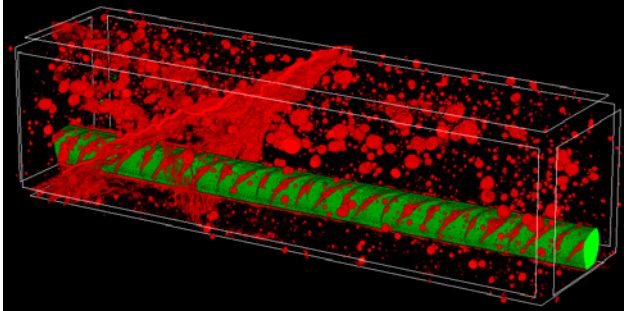
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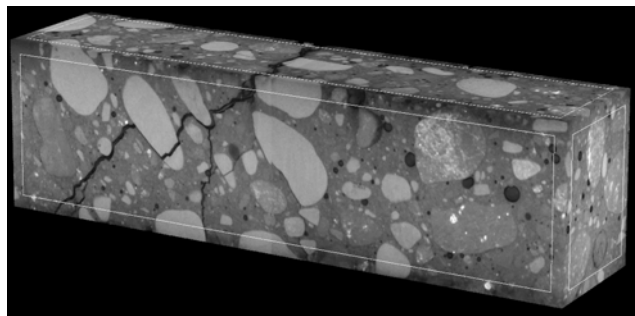
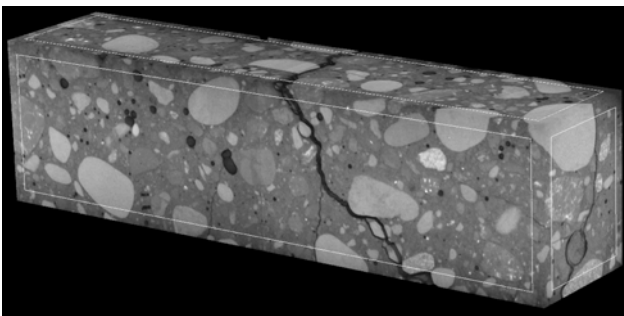
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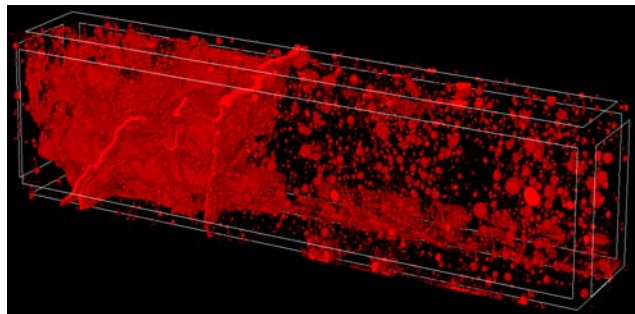
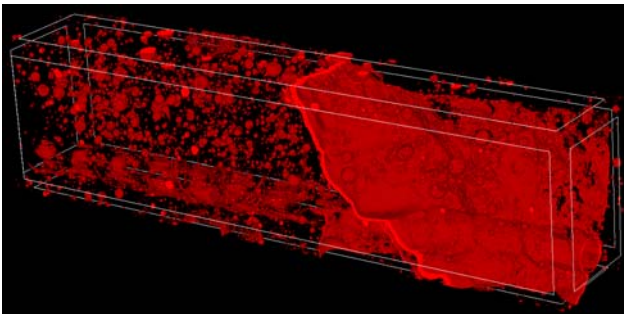
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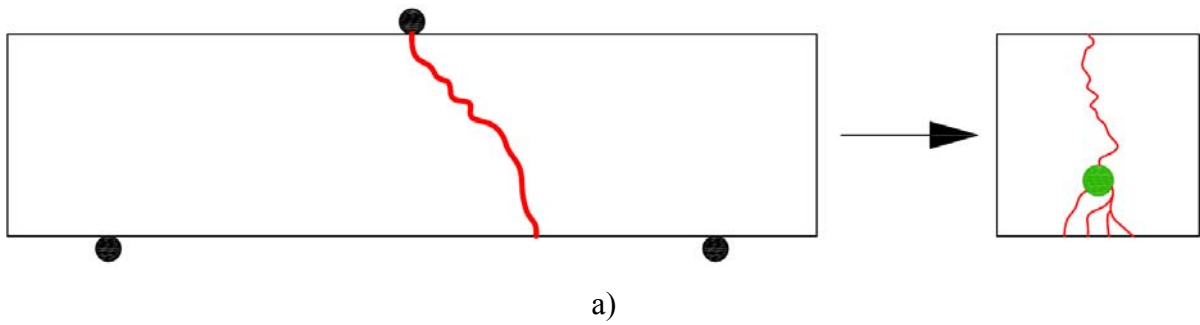
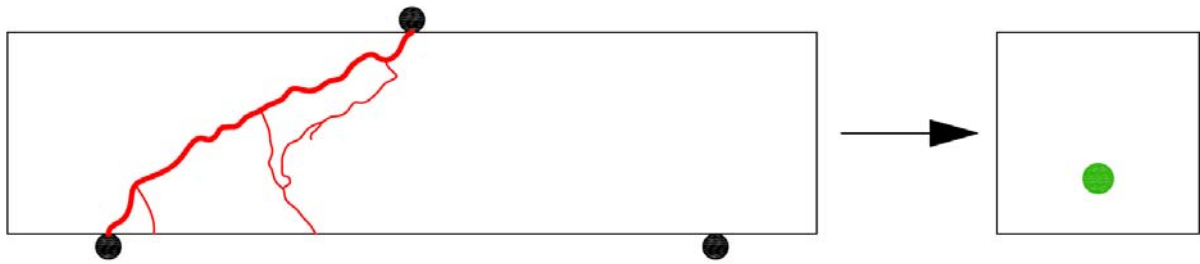
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9 **Figure 8:** Final 3D micro-CT images on 2 sides of long cracked concrete beams ($L=160$ mm)
0 reinforced with: A) steel bar and (B) basalt bar for deflection about $u=1.0$ mm (a) beam front side
1 and b) beam rear side, pores and cracks are in red, steel bar is in green)

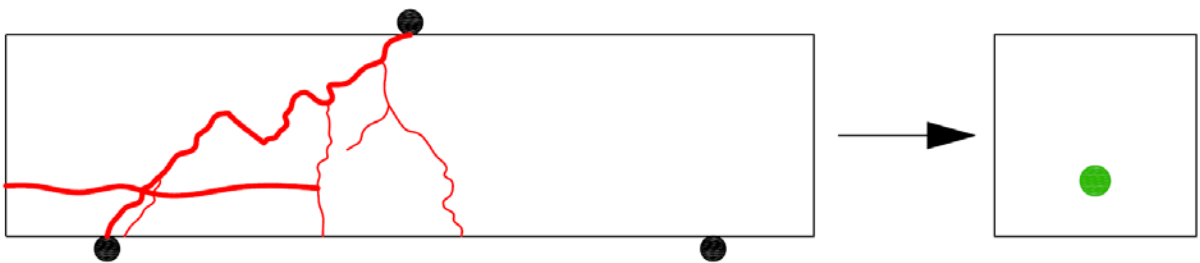
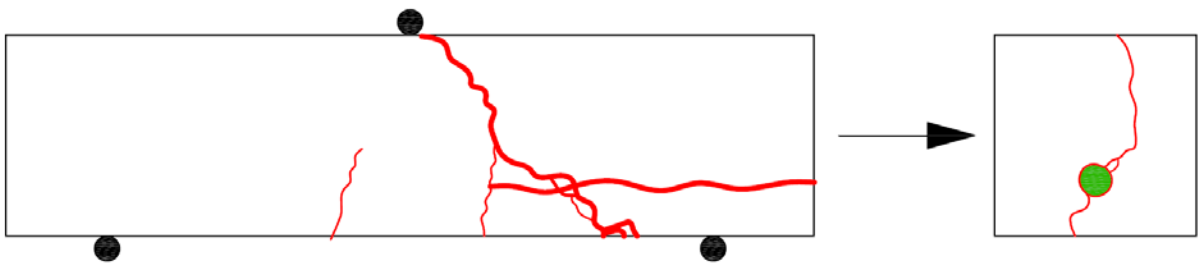
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FIGURE 8



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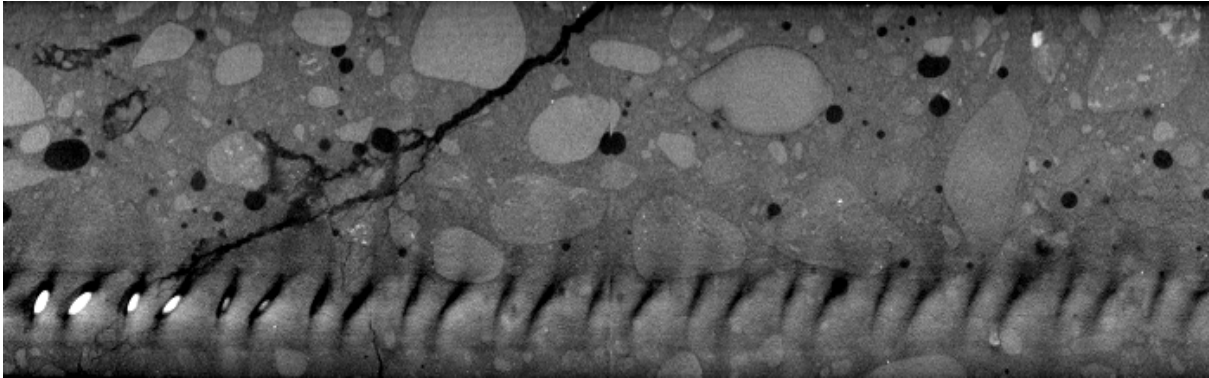


b)

Figure 9: Sketch of final crack pattern in long RC beams ($L=160$ mm) on all sides with: a) steel bar and b) basalt bar (cracks are marked in red, critical shear crack is marked as thick red line, reinforcement bar is marked in green)

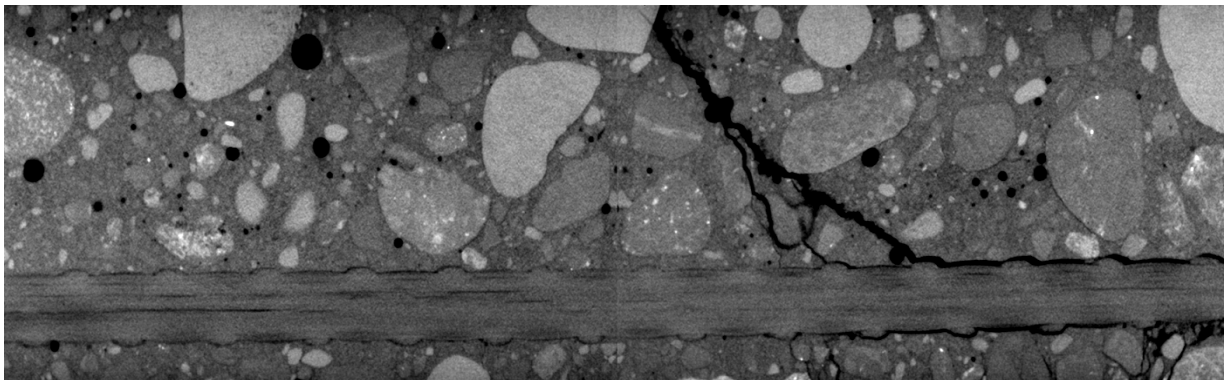
FIGURE 9

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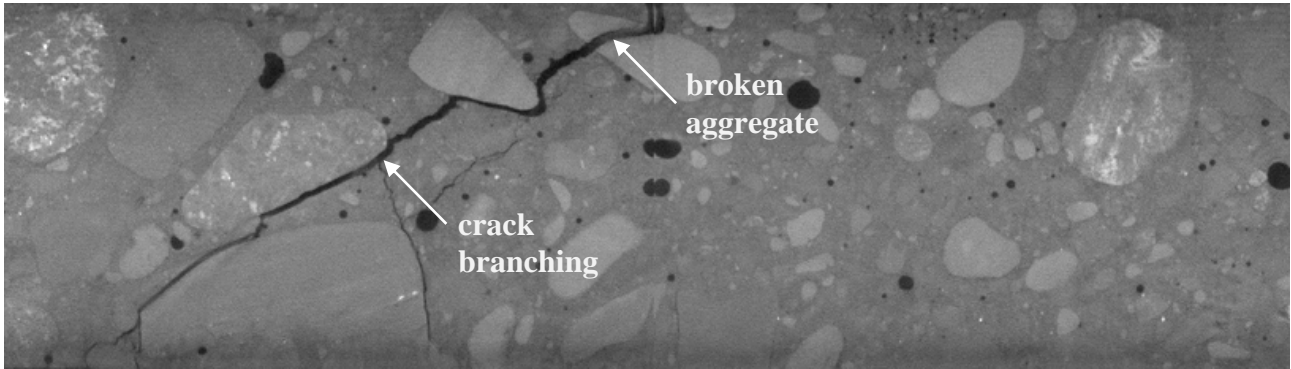
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Figure 10: Vertical cross-section at mid-width of long RC beam ($L=160$ mm) with: a) steel bar and b) basalt bar

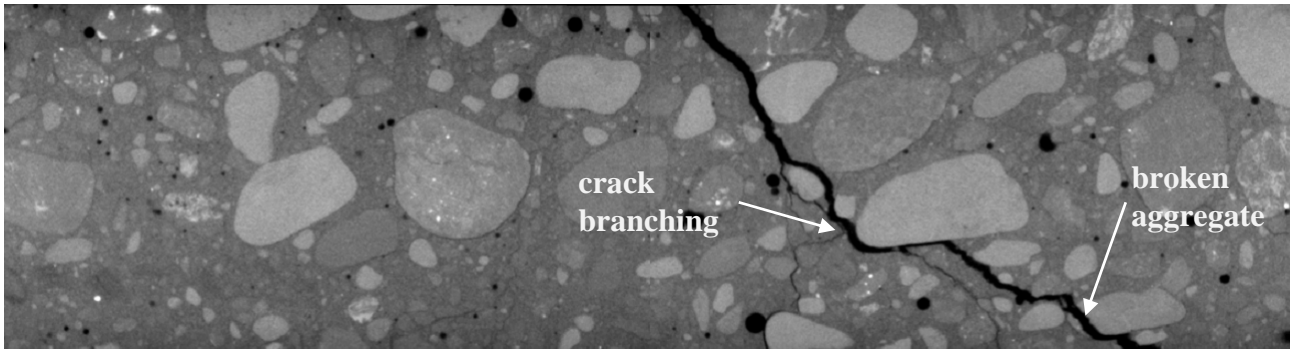
FIGURE 10

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Figure 11: Crack crossing weak aggregate and crack branching in long RC beam ($L=160$ mm) with: a) steel bar and b) basalt bar

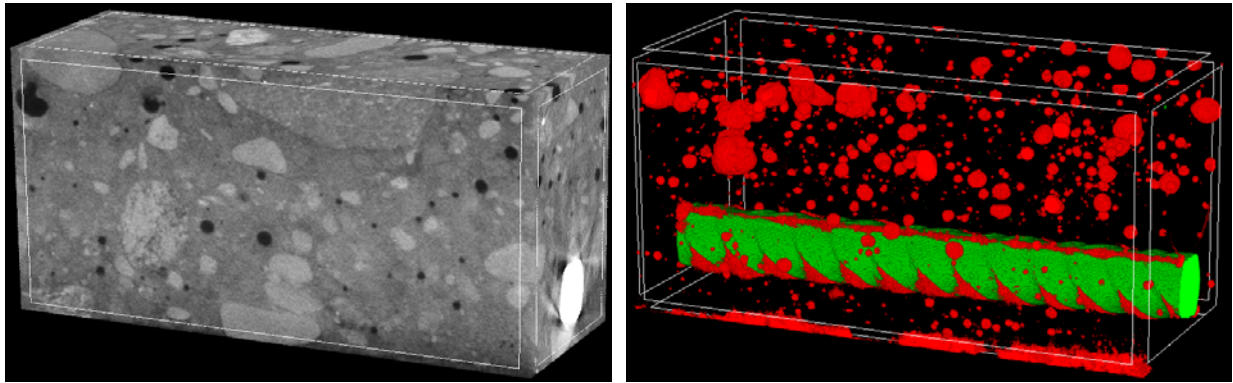
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FIGURE 11

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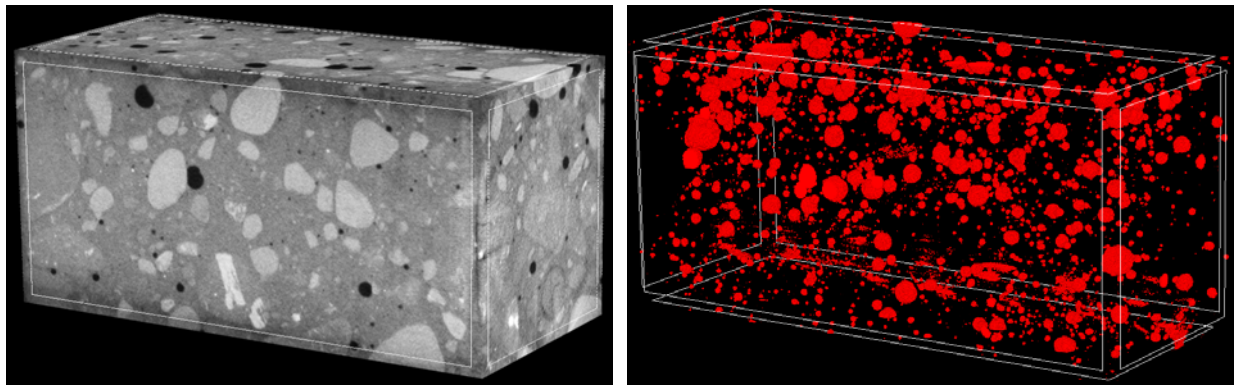
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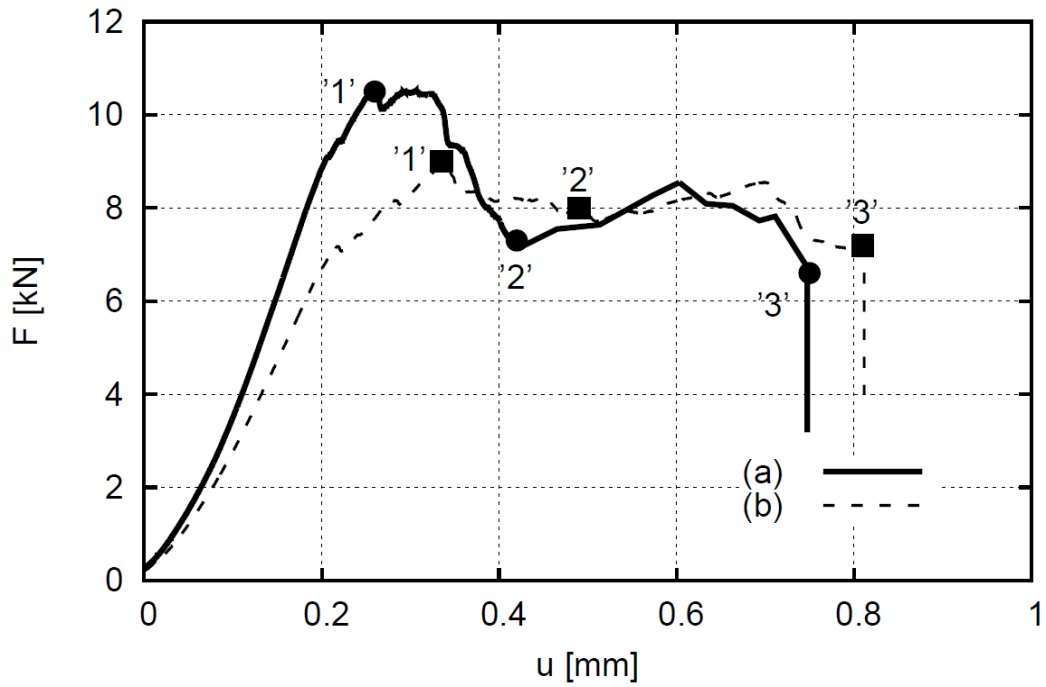
825
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828 **Figure 12:** General view on beams and distribution of pores in 3D micro-CT images of non-cracked short RC beams ($L=80$ mm) before loading reinforced with: a) steel bar and b) basal bar
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FIGURE 12

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Figure 13: Experimental force (F) deflection (u) curve for short RC beams ($L=80$ mm) with:
a) steel bar and b) basalt bar and marked micro-CT scanning points '1'-'3'

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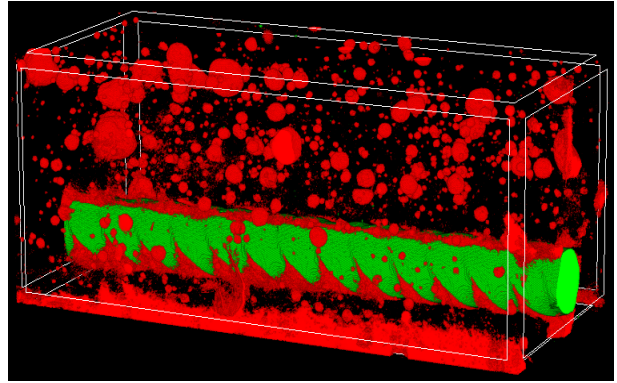
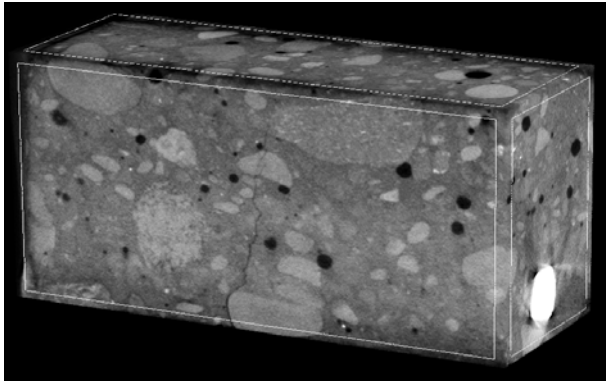
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FIGURE 13

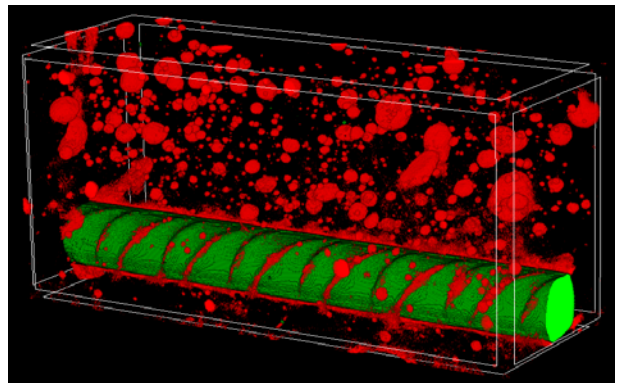
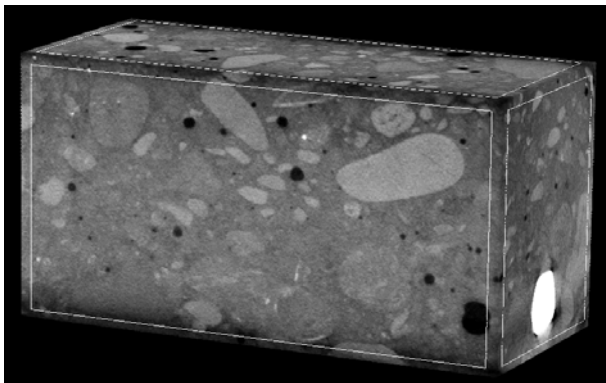
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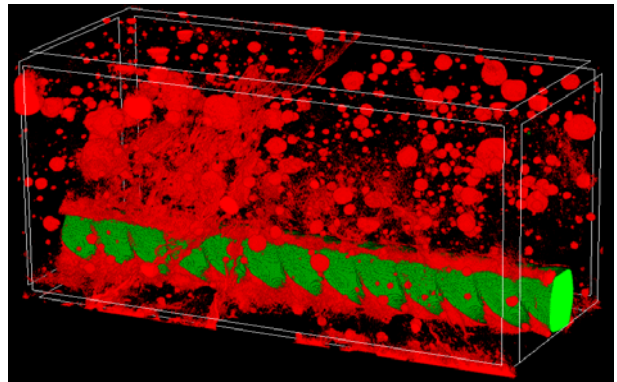
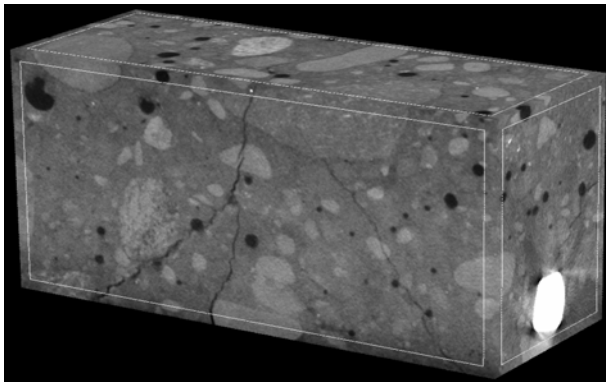


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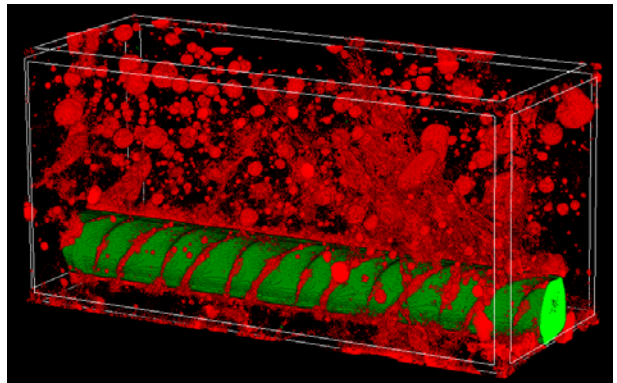
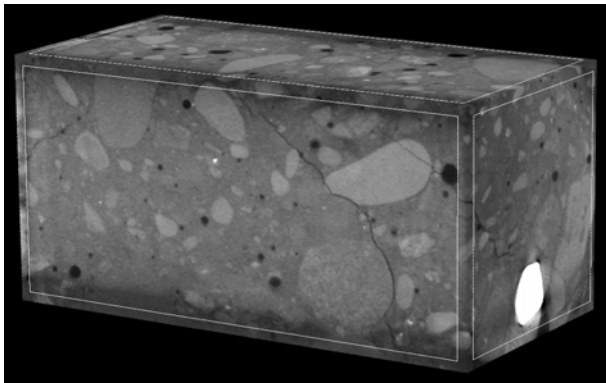
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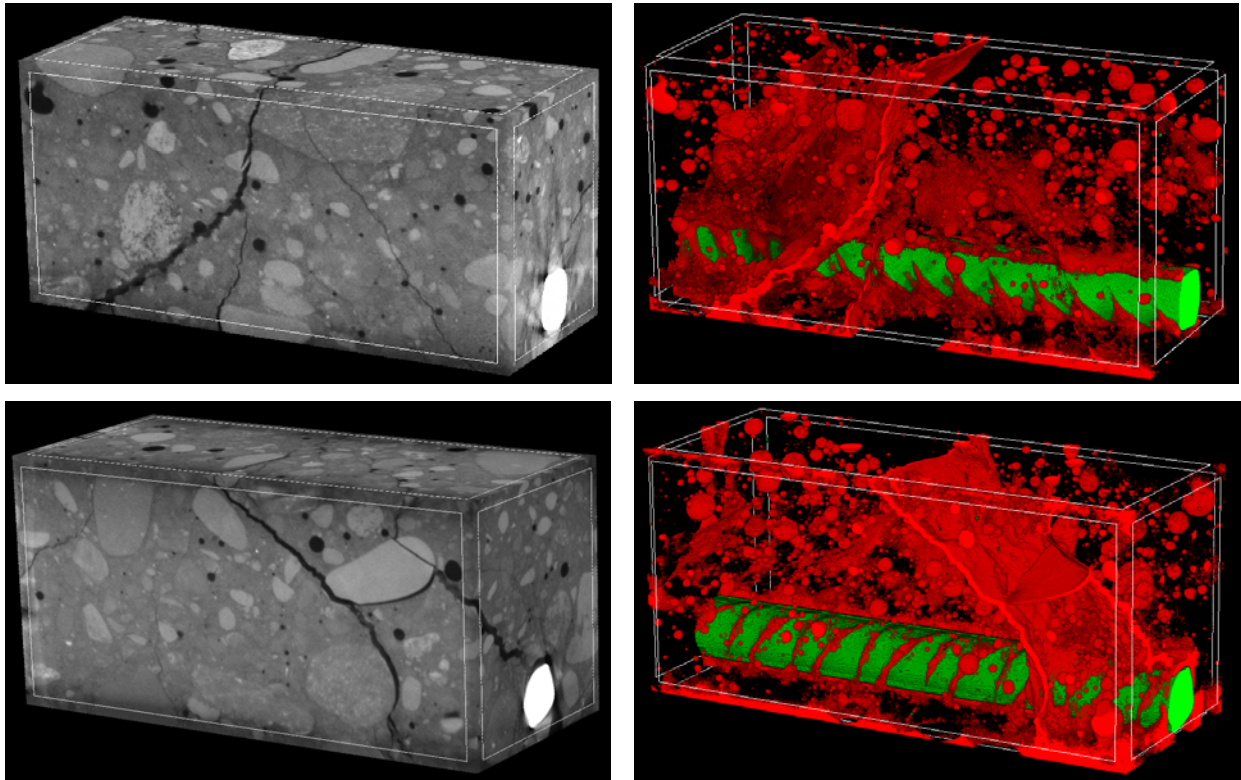


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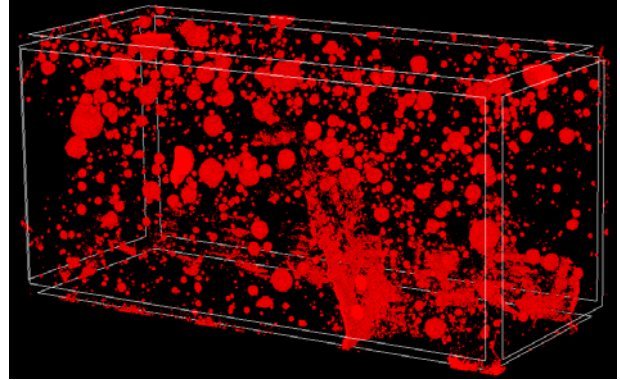
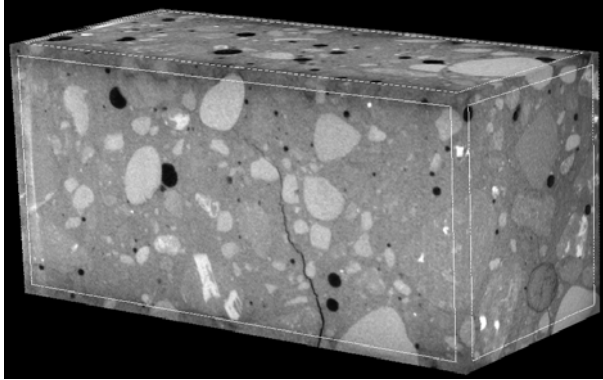
872 **Figure 14:** 3D micro-CT images of short RC beam reinforced with steel bar ($L=80$ mm) on both
873 sides for: a) point '1', b) point '2' and c) point '3' on curve $F=f(u)$ of Figure 13 (pores and cracks
874 are in red, steel bar is in green)

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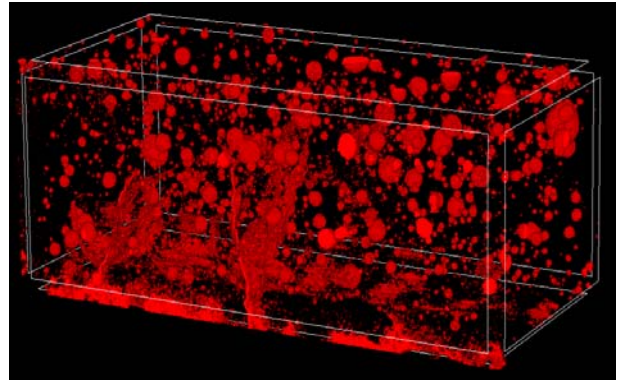
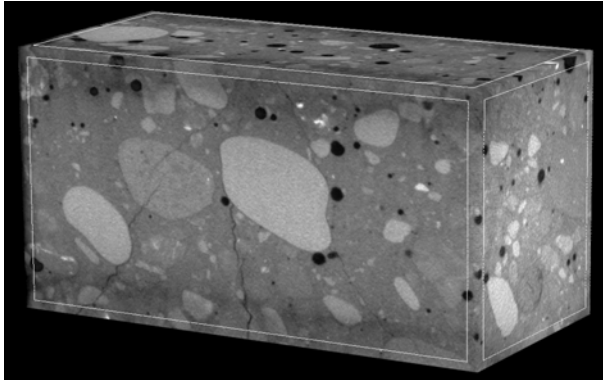
FIGURE 14

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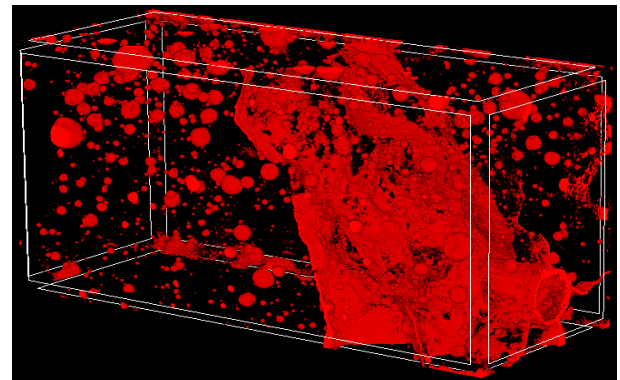
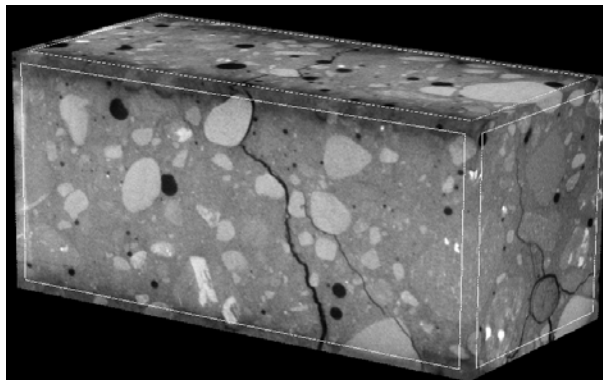
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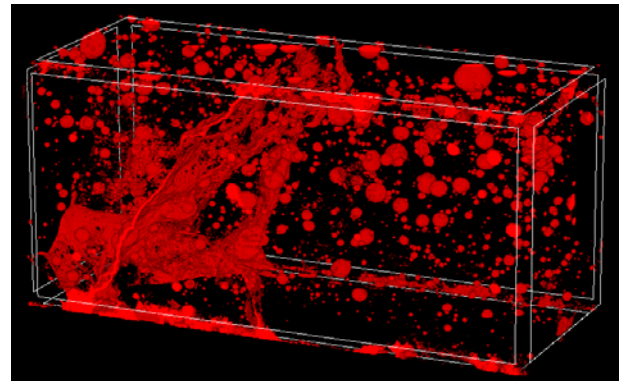
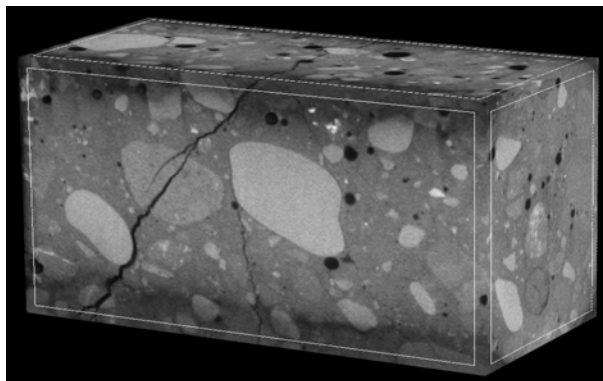
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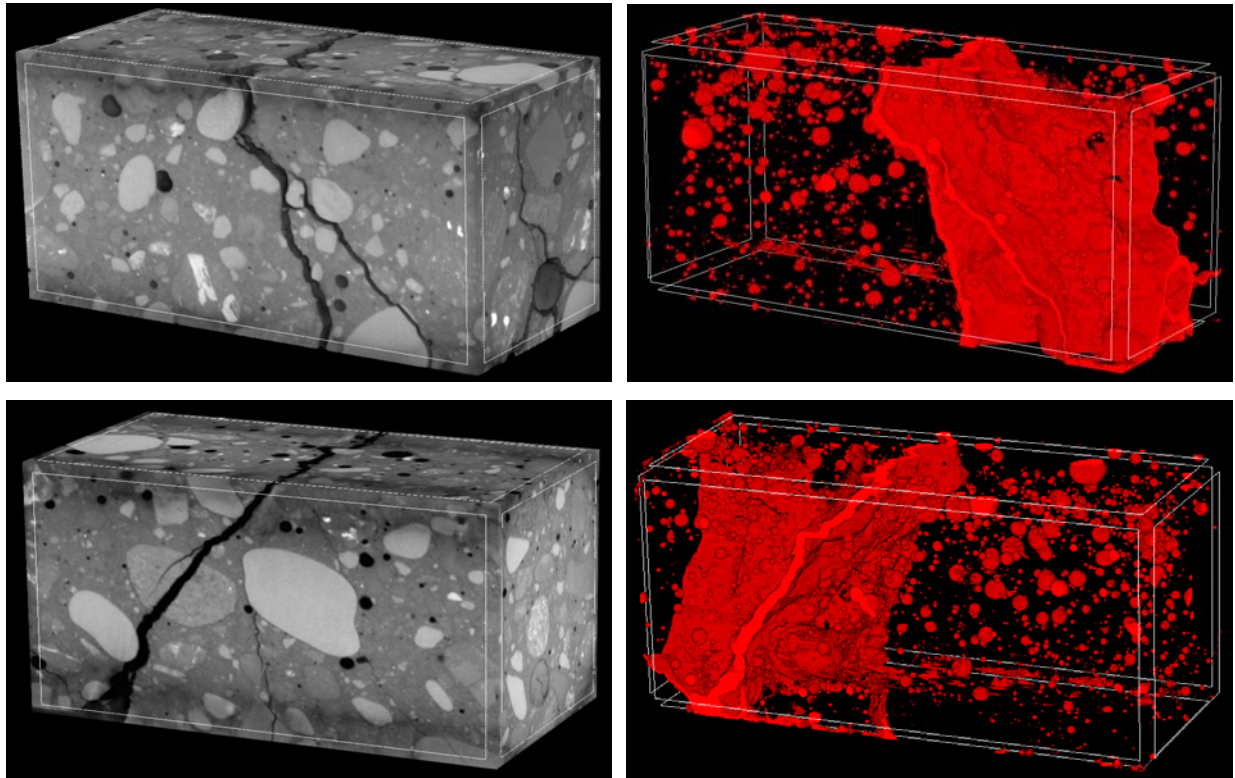


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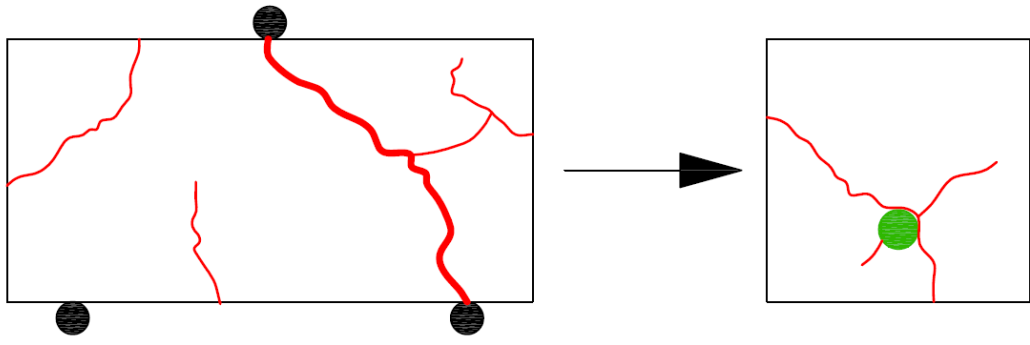
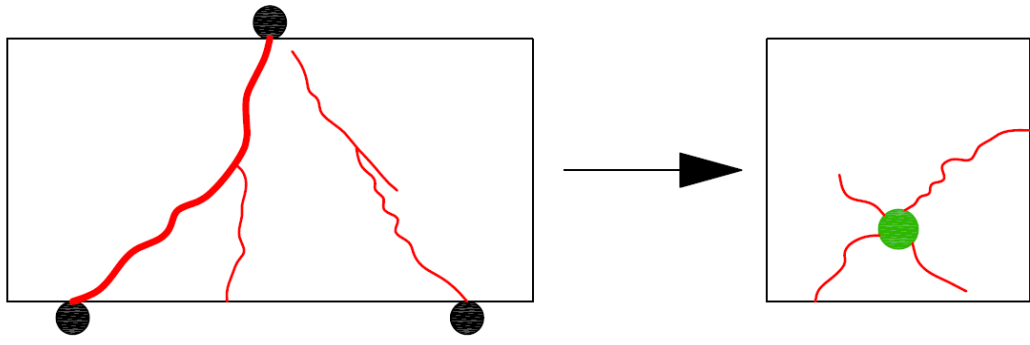
c)

900 **Figure 15:** 3D micro-CT images of short RC beam reinforced with basalt bar ($L=80$ mm) on both
901 sides for: a) point '1', b) point '2' and c) point '3' on curve $F=f(u)$ of Figure 13 (pores and cracks
902 are in red, steel bar is in green)

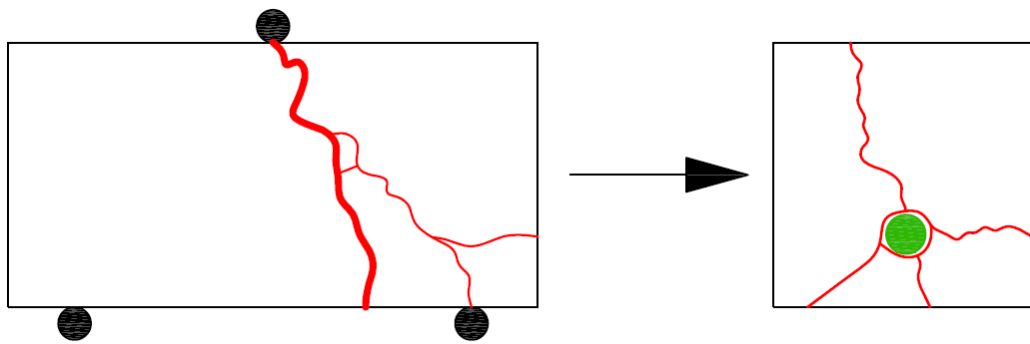
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FIGURE 15

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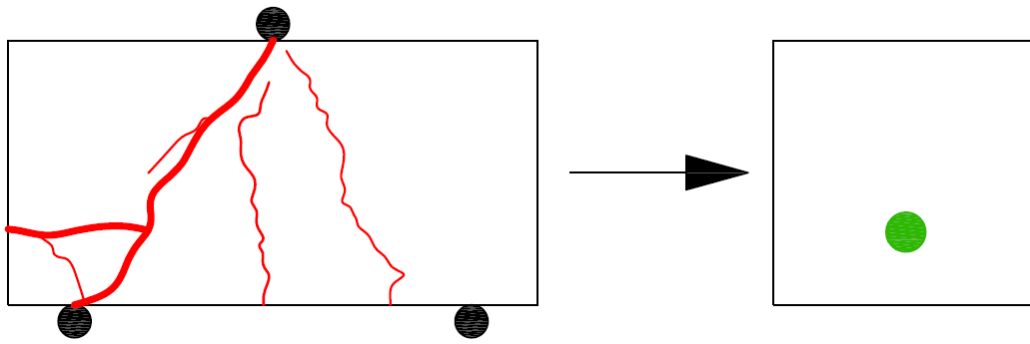


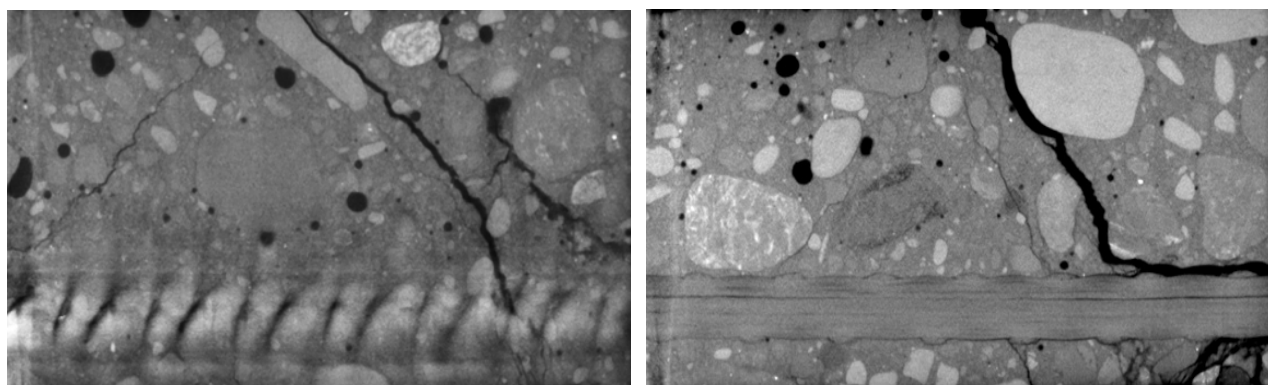
Figure 16: Sketch of final crack pattern for short RC beams ($L=80$ mm) on all sides with: a) steel bar and b) basalt bar (failure crack is marked as thick red line, reinforcement is marked in green)

FIGURE 16

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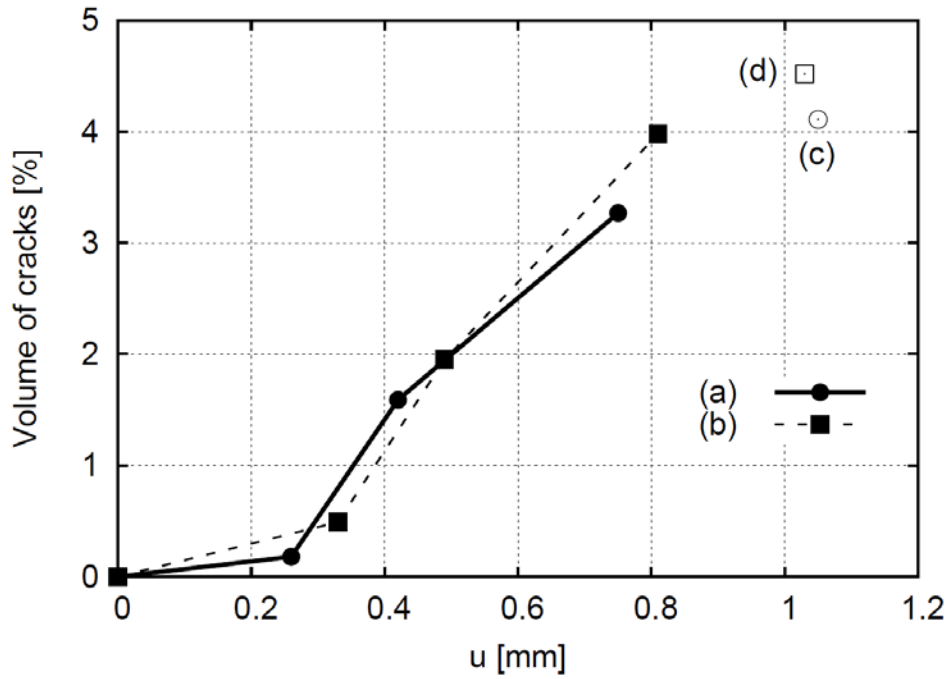
930 **Figure 17:** Vertical cross-section at mid-width of short RC beam ($L=80$ mm) with: a) steel bar and
931 b) basalt bar

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FIGURE 17

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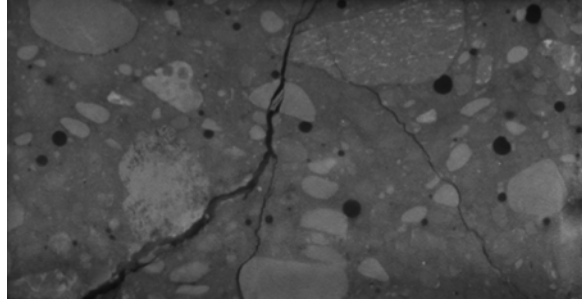
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Figure 18: Relationship between volume of cracks and deflection u during bending for RC beams: a) short beam with steel bar ($L=80$ mm), b) short beam with basalt bar ($L=80$ mm), c) long beam with steel bar ($L=160$ mm) and d) long beam with basalt bar ($L=160$ mm)

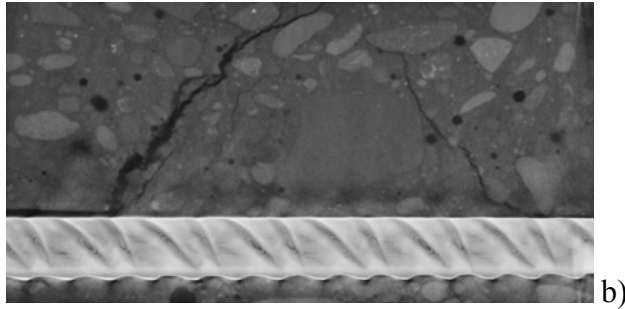
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FIGURE 18

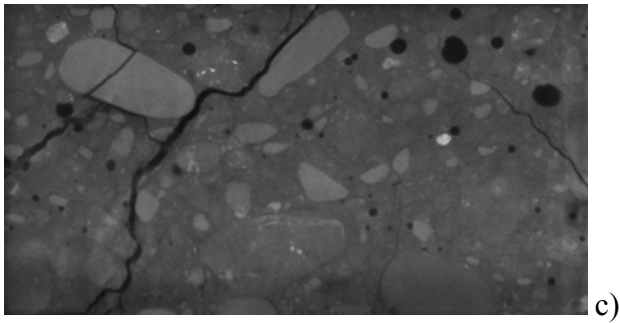
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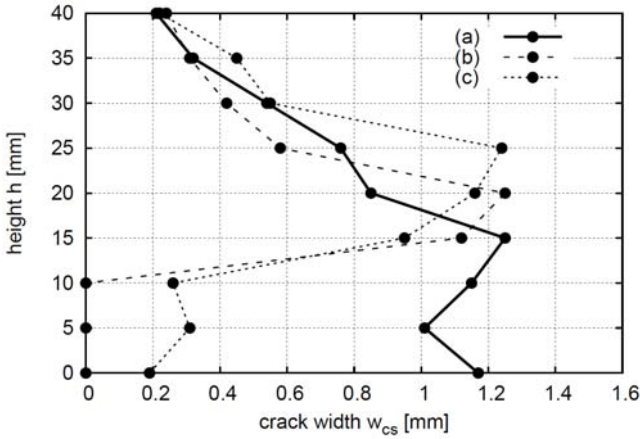


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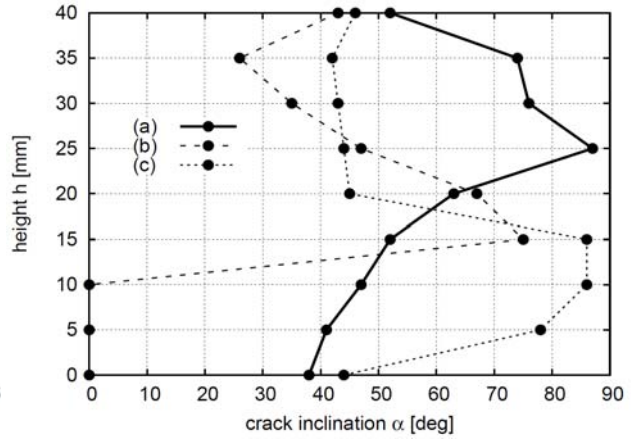


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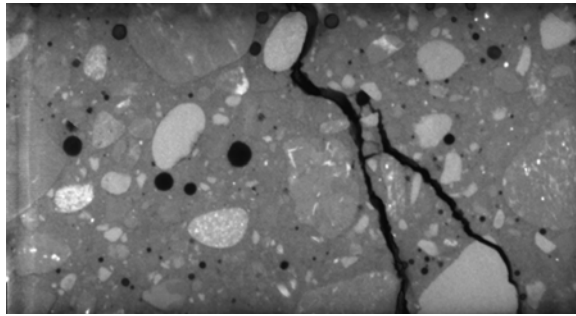
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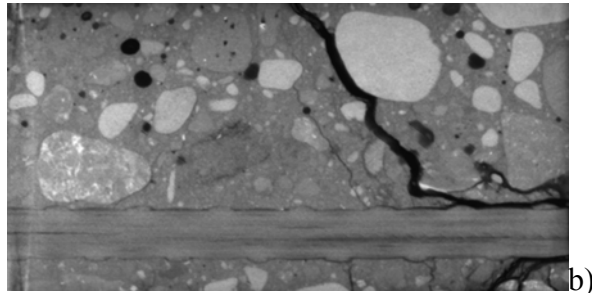
Figure 19: Vertical cross-sections of short RC beam ($L=80$ mm) with steel reinforcement: a) at 5 mm from front side, b) at beam mid-width and c) at 5 mm from rear side and corresponding measurement results of critical shear crack: d) crack width and e) crack inclination angle

FIGURE

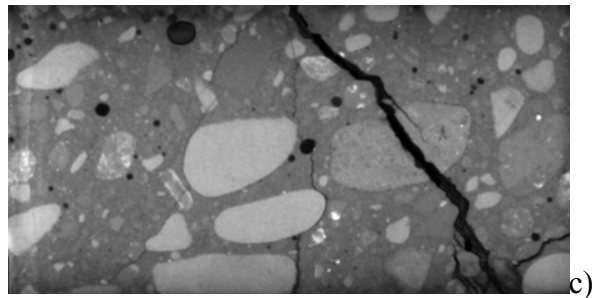
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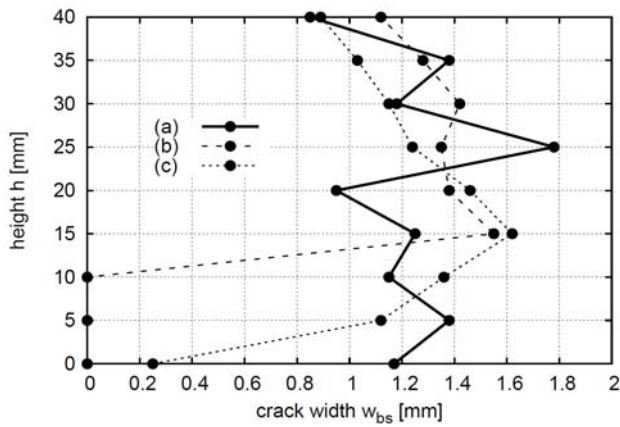


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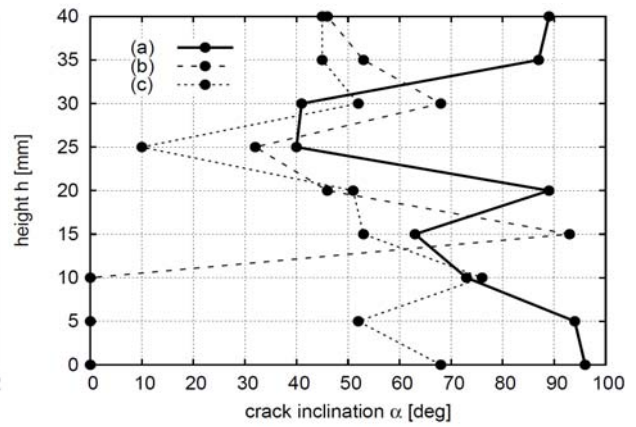


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d)



e)

Figure 20: Vertical cross-sections of short RC beam ($L=80$ mm) with basalt reinforcement: a) at 5 mm from front side, b) at mid-width and c) at 5 mm from rear side and corresponding measurement results of critical shear crack: e) crack width and f) crack inclination angle

FIGURE 20

LIST OF TABLES

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986

Table 1: Concrete mix components (d_{50} – mean particle diameter, d_{max} – maximum aggregate diameter, d - particle diameter)

Concrete components	Volumetric mass of concrete components ($d_{50}=2$ mm and $d_{max}=16$ mm)
Cement CEM II 32 .5R	360 kg/m ³
Sand ($d=0-2$ mm)	650 kg/m ³
Gravel aggregate ($d=2-8$ mm)	580 kg/m ³
Gravel aggregate ($d=8-16$ mm)	580 kg/m ³
Superplasticizer	1.8 kg/m ³
Water	150 kg/m ³

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Table 2: Volume of pores, cracks and maximum crack width in long RC beams ($L=160$ mm) measured by 3D micro-computed tomography at initial and final state

RC beam	Initial volume of pores [%]	Initial volume of closed pores [%]	Initial volume of open pores [%]	Final volume of pores [%]	Volume of cracks [%]	Maximum crack width [mm]
With steel bar	2.64	2.14	0.50	6.75	4.11	1.39
With basalt bar	3.04	2.42	0.62	7.63	4.52	1.68

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1000 **Table 3:** Volume of initial pores in short RC beams ($L=80$ mm) measured by 3D micro-computed
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RC beam	Initial volume of pores [%]	Initial volume of closed pores [%]	Initial volume of open pores [%]
With steel bar	2.67	2.04	0.63
With basalt bar	2.83	2.24	0.59

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1008 **Table 4:** Volume of pores, cracks and maximum crack width in short RC beam ($L=80$ mm) with
 1009 steel reinforcement measured by 3D micro-computed tomography at different loading steps

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Loading point on curve $F-u$ (Figure 13)	Force F [kN]	Deflection u [mm]	Volume of pores and cracks [%]	Volume of cracks [%]	Maximum crack width [mm]
Point '1'	10.46	0.26	2.85	0.18	0.16
Point '2'	7.33	0.42	4.26	1.59	0.48
Point '3'	6.49	0.75	5.94	3.27	1.25

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1020 **Table 5:** Volume of pores, cracks and maximum crack width in short RC beam ($L=80$ mm) with
 1021 basalt reinforcement measured by 3D micro-computed tomography at different loading steps

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Loading point on curve $F-u$ (Figure 13)	Force F [kN]	Deflection u [mm]	Final volume of pores and cracks [%]	Volume of cracks [%]	Maximum crack width [mm]
Point '1'	9.05	0.33	3.32	0.49	0.27
Point '2'	7.98	0.49	4.78	1.95	0.72
Point '3'	7.21	0.81	6.81	3.98	1.78

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