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7. Harnessing digital image correlation system for assessing flexural characteristics of SFRC based on waste ceramic aggregate

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Abstract: The paper presents a research programme focused on steel fibre reinforced concrete based on waste ceramic aggregate. The matrix was reinforced by commercially available engineered steel fibre. Flexural tests were performed using a limit of proportionality method and values of crack mouth opening displacement were followed. The measurements were conducted simultaneously using two independent procedures: a traditional procedure described in the standard and a procedure based on optical measurements with the help of Digital Image Correlation System.

Keywords: aggregate, waste, ceramic, fibre, concrete

7.1. Introduction

Red waste ceramic is one of the key elements of the worldwide volume (particularly in Europe) of construction and demolition waste (Correia, De Brito and Pereira, 2006). It is increasingly recycled and in a form of waste ceramic aggregate (WCA) used for concrete production. So far, successful applications of WCA for concrete production is limited to elements characterized by lesser mechanical performance. Pavement slabs are the most common application of such concretes (Hendriks and Janssen, 2003; De Brito, Pereira and Correia, 2005). Multiple technological problems are associated with using WCA to substitute natural aggregate. There are issues associated both with properties of a fresh mix (workability and stability of a mix) and hardened concrete (small homogeneity of main mechanical properties and limited mechanical characteristics). Red ceramics is porous and thus characterized by very high water absorptivity. Designing methods commonly used for the creation of ordinary concrete mixes are not suitable for WCA based mixes. To overcome these technological and performance issues one can harness internal curing process (Bentur, Igarashi and Kovler, 2001; Suzuki, Seddik Meddah and Sato,

2009) and fibre reinforcement (Domski, 2015; Ponikiewski and Gołaszewski, 2015). Internal curing process which is associated with pre-saturation of porous aggregate guarantees stable and uniform properties of fresh concrete mix during all stages of mixing, handling and casting (Bentur, Igarashi and Kovler, 2001; Suzuki, Seddik Meddah and Sato, 2009). On the other hand, engineered steel fibre proved to be very effective in enhancing limited mechanical characteristics of concretes based on different types of waste aggregates (Katzer, 2008; Łapko, A., Grygo, 2014; Domski, 2015) and thus promising achieving similar improvement in case of WCA concrete (Domski, Katzer and Fajto, 2012). Using fibre reinforcement and WCA simultaneously may prove to be demanding due to irregularities in shape and size of WCA particles which often look like small blades rather than sphere-like grains. Size and shape of an aggregate particles directly influences fibre spacing in hardened concrete (Maidl, 1995; Johnston, 2000). Fibre agglomeration and non-uniform fibre distribution is much more likely to happen in WCA based concrete than in an ordinary mix affecting mechanical performance of the cast elements. Successful merging WCA based concrete and engineered fibre reinforcement would create new opportunities for sustainable development of construction and civil engineering industry. The first objective of the planned study was to evade technological problems with WCA and fibre reinforcement used simultaneously. The second objective was to test cast elements using two methods: traditional limit of proportionality (LOP) method (EN 14651, 2005) and a method based on optical measurements with the help of Digital Image Correlation (DIC) System. DIC is a validated and well-established method for determining displacements in the domain of experimental mechanics and vision-based optical metrology (Malesa and Kujawinska, 2012, 2013). It is being increasingly used to monitor civil engineering structures (Piekarczuk *et al.*, 2012). Nevertheless, feasibility of using DIC systems for testing SFRC is still unknown and needs to be studied. A comparison of results achieved by popular standard LOP method and DIC method bring a clear answer to this question.

7.2. Materials

Raw ceramic waste consisting of different types of broken and crushed ceramic elements (wall blocks, hollow bricks and wire-cut bricks) was used for the "production" of WCA in question. Debris was contaminated by cement mortar and represented the most common type of debris available in Europe (De Brito, Pereira and Correia, 2005). The WCA was created through grinding the debris using an electric industrial grinder. The grinder and grinding procedure were thoroughly described in a previous publication (Cichocki *et al.*, 2014). As a result of grinding all-in-aggregate was achieved (see **Fig. 7.1**). Aggregate fractions characterized by a diameter larger than 32.0 mm and smaller than 1.0 mm were removed. The grading characteristics of prepared WCA was tested using rectangular sieve set (EN 933-1, 2012). Median diameter (Katzer, 2012) and fineness moduli characterizing the WCA were calculated. Loose and compacted bulk densities of the WCA were also tested (. The last tested property of WCA, which is crucial for mix designing and internal curing process, was water absorptivity by weight. All tested properties of WCA are presented in Table 7.1 (Cichocki *et al.*, 2014).

Table 7.1. Properties of WCA

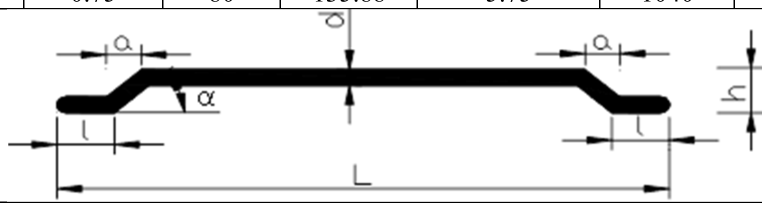
Loose bulk density	Compacted bulk density	Water absorptivity by weight	Median diameter	Fineness modulus by		
[kg/m^3]	[kg/m^3]	[%]	[mm]	Hummel	Abrams	Kuczynski
ρ_{lbd}	ρ_{cbd}	A_w	d_m	m_H	m_A	m_K
948	1170	22	7.4	213.4	7.1	8.2

Fig. 7.1. Waste ceramic all-in-aggregate

Currently there is a dozen of large global producers of engineered steel fibre. Altogether they offer hundreds of steel fibre types differentiated by geometric shape, size, diameter and finishing of surface (Maidl, 1995; Johnston, 2000; Naaman, 2003; Bentur and Mindess, 2007). Over 90% of the steel fibre available on the market is engineered steel fibre with deformed ends, treated surface, twisted, crimped or hooked. A hooked type of engineered steel fibre is the most popular on the global civil and structural engineering market (Domski, 2016). Properties of SFRC based on ordinary aggregates and reinforced by hooked engineered steel fibre are thoroughly tested and described in literature giving the best reference point for comparison and discussion (Zollo, 1997; Katzer and Domski, 2012). The chosen fibre was made of cold drawn wire (Group I with compliance to (EN 14889-1, 2006)) and was characterized by a circular cross-section. Mechanical and geometrical characteristics of the fibre are presented in Table 7.2.

Table 7.2. Mechanical and geometrical characteristics of the engineered steel fibre

Length	Diameter	*Aspect ratio*	*FIER*	Hook	Tensile strength	Ductility
L	d	L/d	$(\Psi \cdot L)/A$*	$l+(a^2+h^2)^{0.5}$**	R_m***	****
(mm)	(mm)	(-)	(-)	(mm)	(MPa)	(№ bends)
60	0.75	80	135.88	5.75	1040	9



* - (Naaman, 2003); ** - (Katzer and Domski, 2012); *** - ISO 6892-1:2009; **** - EN 10218-1:2012

Natural sand washed from all-in-aggregate of post-glacial origin during hydro-classification process was used as fine aggregate. The sand consists of quartz and crystalline rock, dominated by granite. It was thoroughly tested and described in a previous publication (Cichocki *et al.*, 2014). Portland cement CEM I 42.5 meeting the requirements of (EN 197-1, 2011) was utilized as a binder. Tap water in compliance with (EN 1008, 2002) was the last major ingredient. Mixes were modified by 1% of admixture to keep the required consistency. Silica fume modified superplasticizer of type FM and characterized by density of 1.45 g/cm^3 was harnessed as the admixture.

3.3. Procedures

WCA was fully saturated before the use. Mix composition computed for dry aggregates was adjusted to take into account water absorbed by WCA. Due to the fact that proportions of water absorbed by WCA influencing consistency and internal curing were unknown authors were forced to use the traditional "trial and error method". The amount of needed tap water was established on the basis of a required consistency C2 (degree of compactability according to (EN 12350-4, 2009)). The final mix proportions of one cubic meter were as follows: fully saturated WCA – 830kg (the amount of trapped water – 182.6kg), natural sand – 652kg, cement – 307kg, tap water – 92kg, admixture – 3.1kg, giving together the total mass of 1884.1kg. Fibre reinforcement was added in volumes of 0.0%, 0.5%, 1.0% and 1.5%.

Cast specimens were in a form of cubes (150 mm · 150 mm · 150 mm) and prisms (150 mm · 150 mm · 550 mm). All specimens were compacted in two layers using a vibrating table. Curing was divided into two phases. Phase one lasted 24 hours and specimens were kept in moulds covered with polyethylene sheets. Phase two lasted 27 days and specimens were placed in a water tank (temp: +21°C ± 1°C).

Compressive strength and tensile splitting test were both tested on cube specimens. The tests were conducted according to (EN 12390-3, 2009) and (EN 12390-6, 2009) respectively. Flexural tensile strength was tested according to the limit of proportionality (LOP) method (EN 14651, 2005). The three-point flexural test was chosen as the most reliable one in comparison to four-point tests. In case of three-point test, a beam is formed with a notch and the first crack always appears in the vicinity of the mid-span. The crack mouth opening displacement (CMOD) was measured for all tested beams. The residual tensile strength f_R and the responses of SFRC prisms for CMOD equal to 0.5mm, 1.5mm, 2.5mm and 3.5mm were of special interest. The loading rate was equal to 0.2mm/min and load-CMOD curves were registered. The examination results were statistically processed, and values bearing the gross error were assessed on the basis of Grabbs criterion (Bayramov, Taşdemir and Taşdemir, 2004). This testing procedure was thoroughly described in a previous publication (Cichocki *et al.*, 2014). Flexural toughness was assessed for all tested concretes. Flexural toughness is very useful to evaluate the resistance of the fibre composites under dynamic loadings (impact, harmonic, fatigue) (Maidl, 1995; Johnston, 2000; Bentur and Mindess, 2007). During the research programme flexural toughness was understood as total energy absorbed in breaking a specimen in flexure. On the basis of force – deflection relationships achieved during the research programme there were calculated two values of toughness. The first was based on the area up to maximum load, the second was based on the area up to a specified end-point deflection equal to 3.44 mm. Shear strength was tested according to (JCI-SF6, 1984). There were used prism specimens (half-beams leftovers after flexural tests) which were loaded using shear apparatus. During the test, load acts perpendicularly on the specimen at all times. Loading was applied to the specimen continuously without impact. The rate of loading was such that the increase in shear stress was from 0.06 MPa to 0.1 MPa. The objectivity of all conducted experiments was assured by the choice of the sequence of the realization using a table of random numbers.

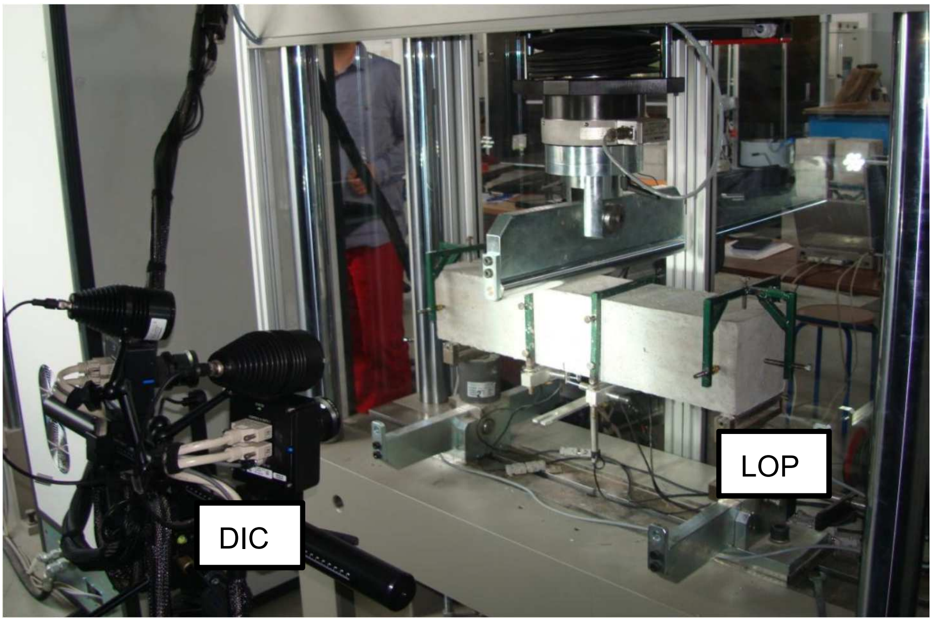


Fig. 7.2. Laboratory set-up used for flexural tests.

The whole process of flexural LOP test was simultaneously followed by DIC procedure. In **Figure 7.2** one can see the set-up of both apparatuses (LOP and DIC) during the flexural test of a prism specimen. DIC apparatus was focused on central (notched) part of a prism. During the research programme commercially available DIC apparatus of German origin was utilized. The apparatus was in a standard configuration offered by the producer. Two cameras were equipped with lenses characterized by the focal length of 2.8/50mm. Pictures were taken with the speed of 1 per second. The cameras' angle setting was equal to 25˚. Cameras were located 334 mm away from each other. The distance to an observed beam was equal to 820mm. The adopted facet size was 19 pixels and facet step was 15 pixels. Two halogen spotlights (20W each) provided by the producer of the apparatus were used to light the tested part of a beam.

DIC is a well-established method for estimation of displacements in experimental mechanics and optical metrology (Malesa and Kujawinska, 2012, 2013). The method was introduced in the early 1980s. Since then the quality of digital images has improved enormously and harnessed algorithms have gone through multiple mayor modifications. The technological development of DIC enabled new areas of its application. DIC technique entered civil and structural engineering and are being more and more often utilized for testing specimens and most recently whole structures (Piekarczuk *et al.*, 2012). The main advantage of using DIC technique in comparison to traditional gauges and sensors techniques is the ability to observe thousands of points simultaneously in 3-D. Using such technique in case of SFRC elements seems to be very promising.

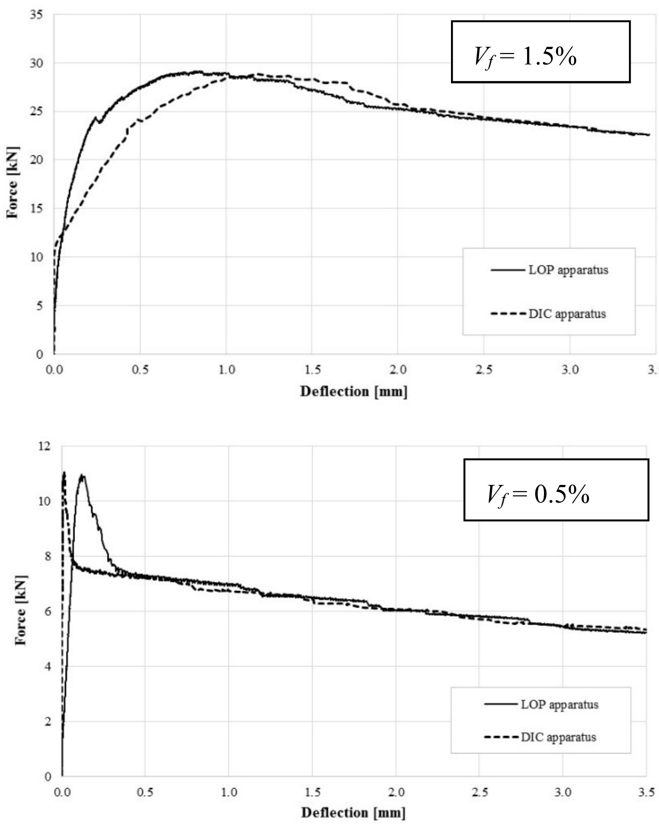


Fig. 7.3. Flexural characteristics of tested SFRC.

SFRC is much more demanding in testing than ordinary concrete or even traditionally reinforced concrete elements. Comparison of results achieved by means of standardized LOP method and by DIC method would give a preliminary answer to the question if LOP method could be substituted by DIC method. There is also very large potential space for developing brand new testing methodology of SFRC based solely on DIC method. Such a new testing procedure would be very useful in case of SFRC based on waste aggregate which is even more difficult for testing than ordinary SFRC while using traditional standardized methods. During the research programme commercially available DIC apparatus with dedicated computer and software was used.

7.4. Results and discussion

Results of density, compressive strength, splitting tensile strength and shear strength are presented in **Table 7.3**. In case of all tested strengths fibre reinforcement significantly improves the mechanical characteristics of WCA concrete. Changes in values of splitting tensile strength and shear strength mirror the behaviour of ordinary concrete reinforced by engineered steel fibre (Maidl, 1995; Johnston, 2000; Bentur and Mindess, 2007). Compressive strength was improved by 11.8% and 29.4% for fibre volume of 0.5% and 1.5% respectively. These values are much higher in comparison to ordinary concrete reinforced by the same volume of hooked steel fibre (Zollo, 1997; Domski, 2016).

Table 7.3. Mechanical properties of tested SFRC

<table>
<tr><td colspan="3" rowspan="2">Properties</td><td colspan="3">Fibre V_f [%]</td></tr>
<tr><td>0.0</td><td>0.5</td><td>1.5</td></tr>
<tr><td colspan="3">Density of hardened concretes [kg/m^3]</td><td>2001</td><td>2006</td><td>2096</td></tr>
<tr><td rowspan="3">Strength [MPa]</td><td colspan="2">Compressive</td><td>39.1</td><td>43.7</td><td>50.6</td></tr>
<tr><td colspan="2">Splitting tensile</td><td>3.1</td><td>3.4</td><td>5.4</td></tr>
<tr><td colspan="2">Shear</td><td>5.0</td><td>7.3</td><td>11.6</td></tr>
<tr><td rowspan="4">Flexural toughness [kN·mm]</td><td rowspan="2">LOP</td><td>Maximum loading force</td><td>0.0</td><td>0.8</td><td>20.4</td></tr>
<tr><td>Deflection 3.44mm</td><td>0.0</td><td>22.2</td><td>86.6</td></tr>
<tr><td rowspan="2">DIC</td><td>Maximum loading force</td><td>0.0</td><td>0.6</td><td>27.6</td></tr>
<tr><td>Deflection 3.44mm</td><td>0.0</td><td>22.7</td><td>83.2</td></tr>
</table>

In Figure 7.3 flexural characteristics of tested SFRC are presented in a form of force-deflection relations. Two sets of force-deflection relation are available for each SFRC: prepared on the basis of LOP apparatus and DIC apparatus. DIC based relation was created using multiple strain images. One can follow the whole process of crack forming, crack opening and destruction of a specimen in these images. DIC strain images for the start of the flexural test, crack forming and ultimate destruction of the specimens are presented in Figure 7.4 and Figure 7.5 for prism with V_f = 0.5% and 1.5% respectively. The images are prepared in artificial colours mirroring strain values from 0% to 100%. Both sets of relations (obtained from LOP and DIC procedures) enabled calculations of flexural toughness (see Table 7.3) and residual strengths (see Table 7.4). Flexural toughness representing the amount of energy needed to ultimately destroy a SFRC specimen is almost the same for LOP and DIC results in case of low (V_f = 0.5%) volume of added fibre. For the large volume of fibre (V_f = 1.5%) results differ significantly. DIC gives the value of flexural toughness larger than LOP for maximum loading (by 35.3%) but smaller for deflection of 3.44mm (by 3.9%). The residual strengths f_{R1}, f_{R2}, f_{R3}, f_{R4} were calculated according to (EN 14651, 2005) and they correspond to values of Crack Mouth Opening Displacement (CMOD) of 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm respectively. Strength classes were assigned to tested SFRC using value of f_{R1} (representing the strength interval) and the f_{R3}/f_{R1} ratio (codified by letters *a*, *b*, *c* and *d* - *fib* Model Code 2010). This classification represents the most common cases of hardening and softening of SFRC (where *a* stands for "pure" softening and *d* stands for "pure" hardening). Traditional rebar and stirrup reinforcement substitution was assessed using the f_{R3}/f_{R1} and f_{R1}/f_{LOP} ratios. According to the *fib* Code f_{R1} and f_{R3} are significant for service limit states (SLS) and ultimate limit states (ULS) respectively. The traditional reinforcement substitution is enabled if the f_{R3}/f_{R1} and f_{R1}/f_{LOP} ratios are larger than 0.5 and 0.4 respectively.

Table 7.4. Residual strengths, strength class and traditional reinforcement substitution

Residual strengths (MPa)	V_f = 0.5%		V_f = 1.5%	
	LOP	DIC	LOP	DIC
f_{LOP}	4.3	4.6	6.7	5.4
f_{R1}	3.1	3.0	11.3	9.8
f_{R2}	2.9	2.8	12.0	11.9
f_{R3}	2.7	2.5	10.4	10.5
f_{R4}	2.5	2.3	9.8	9.7
Strength class classification and traditional reinforcement substitution				
$f_{R3}/f_{R1} > 0.5$	0.87	0.83	0.92	1.07
$f_{R1}/f_{LOP} > 0.4$	0.72	0.65	1.69	1.81
Class	3*b*	3*b*	11*c*	9*c*
Substitution	enabled	enabled	enabled	enabled

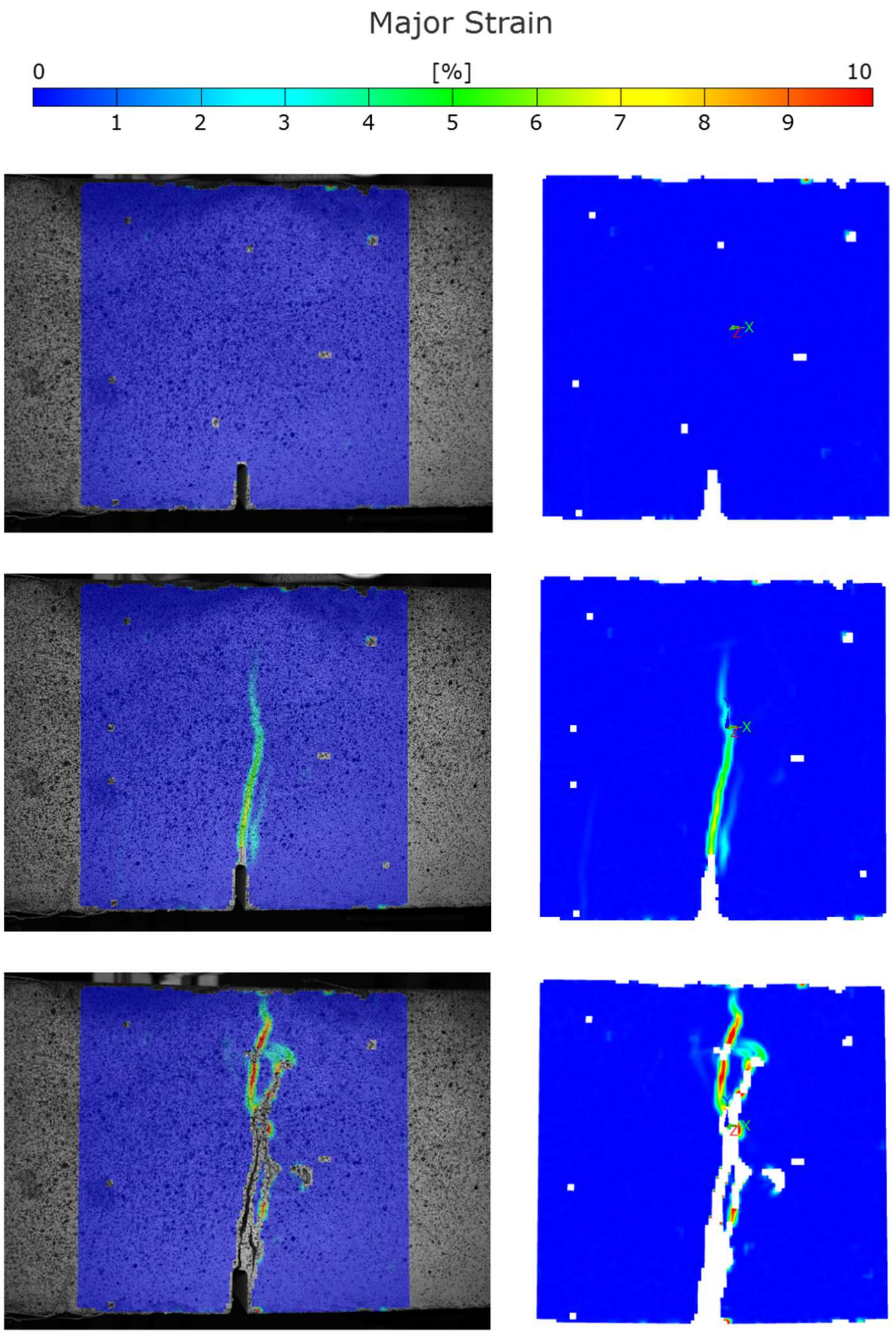


Fig. 7.4. Crack opening – prism with $V_f = 0.5\%$ – DIC strain image

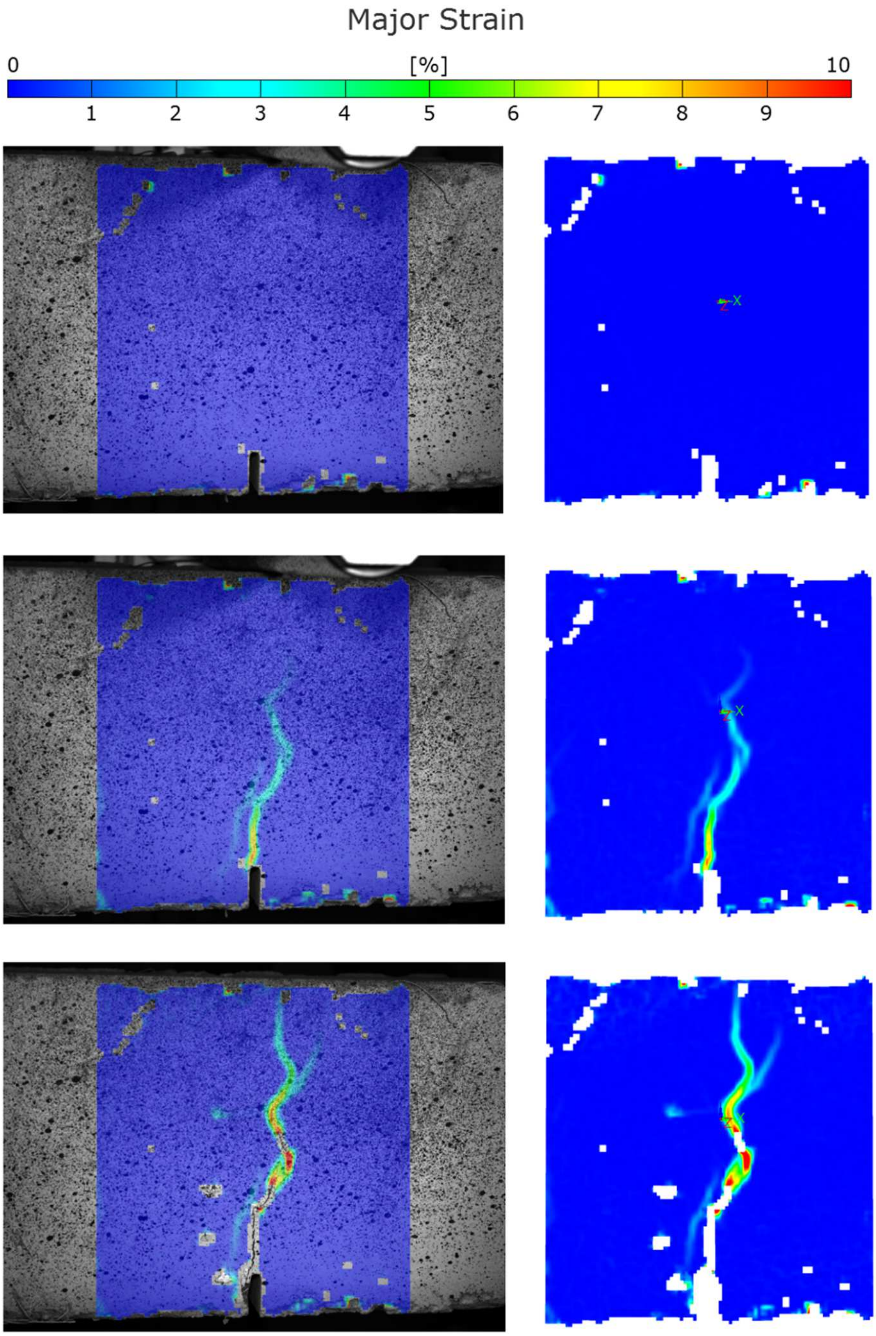


Fig. 7.5. Crack opening – prism with $V_f = 1.5\%$ – DIC strain image

Both tested SFRC achieved results by LOP and DIC methods enabling a traditional reinforcement substitution. All residual strengths calculated for SFRC with V_f equal to 0.5% are very similar for both methods. In case of SFRC reinforced by 1.5% of fibre DIC method gave lower values of f_{LOP} (by 18.4%) and f_{R1} (by 13.3%) and thus significantly influencing strength class and assessment of traditional reinforcement substitution. Differences in values of other residual strengths are less than 1%. Following the force-deflection relations in Figure 7.3 one can notice that the elastic part of the curves is much steeper for DIC method and influencing the initial part of the plastic part of the curves. For large deflections both methods gave the same relations. This phenomenon is probably associated with accuracy of the DIC method which was originally developed for testing steel and other metals. SFRC, as quasi-plastic material behaves in a very specific way which is challenging for DIC.

7.5 Conclusions

The conducted research programme allows to draw the following conclusions:

- Flexural characteristics of SFRC based on WCA enables traditional reinforcement substitution.
- Force-deflection characteristics achieved by LOP and DIC methods are similar, but differences (especially in case of elastic part of the relations) are noticeable.
- Flexural toughness calculated for LOP and DIC results is very similar in case of low volume of added fibre ($V_f = 0.5\%$).
- There are differences in calculated values of flexural toughness for LOP and DIC results for large volume of added fibre ($V_f = 1.5\%$) ranging from -3.9% to +35.3%.
- LOP and DIC method give very similar results in case of low volume of added fibre ($V_f = 0.5\%$) resulting in assignment of the same strength class.
- LOP and DIC methods give significantly different results in case of large volume of added fibre ($V_f = 1.5\%$) resulting in assignment of a different strength class.
- DIC method can be used for testing SFRC, but caution and awareness of DIC accuracy should be maintained.
- Research programmes should be conducted focusing on different SFRC, steel fibre volumes and fibre types utilizing LOP and DIC testing methods.

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