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Techniques to monitor the crack width and the neutral axis position of steel fiber reinforced concrete beams subjected to bending

Técnicas para monitorar a abertura de fissura e a posição da linha neutra em vigas de concreto reforçado com fibras de aço submetidas à flexão

   

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Abstract

In this work, three different techniques are investigated for measuring and monitoring the crack-mouth opening displacement and the depth of the neutral axis of six beams, such as: electrical resistance strain gauges, digital image processing, and displacement transducers. Steel fibers reinforced concrete beams were subjected to bending and the load, displacement, compressive strain, crack-mouth opening displacement and depth of the neutral axis were monitored. For displacement transducers and digital image processing techniques it is showed equations to be used to correct the crack-mouth opening displacement and the depth of the neutral axis due to the beam displacement and rotation. The results show that electrical resistance strain gauges and displacement transducers techniques are more efficient to monitor the depth of the neutral axis. Using the technique of digital image processing it is observed that a small error in the measurement of grid deformations causes a great error in the measurement of the neutral axis position. The crack-mouth opening displacement is measured only by image processing and displacement transducers techniques, and a good agreement between the results from these two techniques can be seen. It is verified that the best technique is the displacement transducers, because with this it is possible to monitor and measure, both, the crack-mouth opening displacement and the depth of the neutral axis. Additionally, the displacement transducers technique is easier to be applied.

Keywords: *steel fiber reinforced concrete, steel fiber, depth of neutral axis, crack width, flexural test.*

Resumo

Neste trabalho, três diferentes técnicas para medir e monitorar a abertura de fissura e a posição da linha neutra são investigadas, sendo elas: *strain gauges*, análise digital de imagens e transdutores de deslocamento. Foram ensaiadas à flexão vigas de concreto reforçado com fibras de aço, nas quais foram monitoradas as cargas, os deslocamentos, as deformações à compressão, a abertura de fissura e a posição da linha neutra. Para as técnicas dos transdutores de deslocamento e da análise digital de imagens são apresentadas formulações matemáticas que devem ser empregadas para a correção dos valores de abertura de fissura e posição da linha neutra em função do deslocamento e do giro da viga durante o ensaio de flexão. Os resultados mostraram que as técnicas do *strain gauges* e dos transdutores de deslocamento foram mais eficientes para monitorar a posição da linha neutra. Na técnica da análise digital de imagens observou-se que um pequeno erro na medição das deformações nos pontos da grade de referência colada na lateral da viga ocasionou um grande erro no valor da posição da linha neutra medido. A abertura de fissura só foi possível ser medida por meio das técnicas dos transdutores de deslocamento e da análise digital de imagens, sendo que ambas apresentaram bons resultados. Verificou-se que a melhor técnica para monitorar tanto a posição da linha neutra quanto a abertura de fissura foi a dos transdutores de deslocamento, além de ser a técnica que apresenta maior facilidade de aplicação.

Palavras-chave: *concreto reforçado com fibras de aço, fibras de aço, abertura de fissura, posição da linha neutra, ensaio de flexão.*

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1. Introduction

The cement dies, such as Portland cement concrete, are brittle, with low tensile strength and low tensile strain capacity. The introduction of steel fiber in the common concrete promotes two important effects: first, it contributes on composite reinforcement when subjected to all kinds of loads, which induces the tension stress, bending and shear and, in second place, it improves the ductility and tenacity of the concrete [1]. An important reason for the addition of discontinuous steel fiber in the concrete die is to improve concrete response after cracking, that is, improve its energy absorption capacity (tenacity) and apparent ductility, and also provide crack resistance and crack control [2].
Therefore, some researchers have developed studies referring behavioral assessment after the cracking of steel fiber reinforced concrete (SFRC), aiming, mainly, estimate the load-displacement curves when subjected to bending effort [3,4,5]. These models are based on the equilibrium of forces in the cracked section from building of tension and deformation diagram in function of the displacement and crack-mouth opening of beam. It is admitted, in these models, the formation of a single crack-mouth in the center of beam spam and formation of plastic hinge in the crack end-point.
In order to verify the validity of theoretical models it is necessary to compare its responses with the results from experimental tests of SFRC beams. It becomes fundamental to conduct the SFRC beams flexural tests in which loads, displacements, strains and crack-mouth openings are monitored during the tests. The load and displacement monitoring is routinely performed in SFRC beams flexural tests and thereupon the scientific community already masters the equipment and procedures for it. However, the monitoring of crack-mouth opening/crack width is not carried out in such frequency on SFRC beams flexural tests and besides that there is no consensus among the researchers about the best way to monitor it. It is verified in some experimental works the employment of displacement transducers for measurement of crack width. Robins et al.[6] have innovated the researches regarding the monitoring of crack width while using digital imaging for this purpose. With this technique, which uses photo images for measuring the crack-mouth opening and is denominated "grid methods", the authors managed to measure the crack width of up to 0.2 mm.
In the light of it, this work has as its main objective to evaluate three different techniques: strain gauges, displacement transducers and digital image processing in order to monitor the crack-mouth opening and the depth of neutral axis during the SFRC beams flexural test.

2. Materials and experimental program

2.1 Manufacturing of beams

For the evaluation of these three techniques for measuring the crack width and neutral axis position it was necessary the manufacturing of steel fiber reinforced concrete beams which were subjected to the flexural test. 6 beams were cast in the dimension of 100x130x400mm, being that these beams have centralized to the two sides a 15 mm depth notch to ensure the cracking of beam in the center of the spam and facilitate the measuring of crack width, according to Gava, Pieri and Prudêncio Jr.[7] proposal. For the beams acqusition, there were cast concrete plates of 100 mm height, from which are sawed 3 beams of each plate. The concrete used for plates casting presented a cement minimum consumption of 430 kg/m^3 and 100 kg/m^3 content of steel fiber. The fiber used was hooked-ended steel fiber, with 30 mm of nominal length, 0.62 mm diameter and, therefore, with an aspect ratio of 48.38.

Figure 1 – Beam prepared for testing

2.2 Bending test of beams – displacements and load monitoring

The beams were subjected to four point bending tests, being monitored the loads, displacements, compressive strains and crack width. The test configuration consisted in support the beam onto two corbels and applying the loading through two other corbels positioned in the upside of beam, in the spam mid-third part. For load application, there were used a Shimadzu brand machine, by means of which was possible to apply a constant or upward displacement of 0.5 mm/min of the piston. The load reading was made by means of load cell with up to 50 kN capacity. The displacement was measured by means of two displacement transducers placed in the central upper part of each one of the beam sides, in order to the measured displacement corresponds to the average of read values. The beam prepared for testing, with the equipments for monitoring loads, displacements, strains and crack width can be viewed in Figure 1.

2.3 *Beams bending test – monitoring of specific deformations*

The evaluation of compressive strains was made by means of strain gauges bonded in the lateral face of beams. On each side of beam there were placed two strain gauges.
Knowing the compressive strains of the concrete in a certain height of beam, for the two points in which the strain gauges were placed, it was possible to determinate the region in certain beam point where the compressive strain is zero, being that this point was considered as neutral axis position in a certain moment of testing. This was made with strain gauges data of each side of beam, being used for analysis the neutral axis position calculated by the average of values determined on each side of the beam. With these data, it was possible to correlate the neutral axis position with the displacement of beam. The value for neutral axis position varies from zero to 50 mm counting from the beam top.

2.4 Bending test of beams – crack width monitoring

The crack width was monitored in two manners: by means of displacement transducers and through digital image processing.
The techniques for monitor crack width and depth of neutral axis employed in this work were defined based on equipment available in laboratory in which the tests were carried out. Other technique that could be tested is the using of clip gauges, however it was not employed due to lack of such equipment.

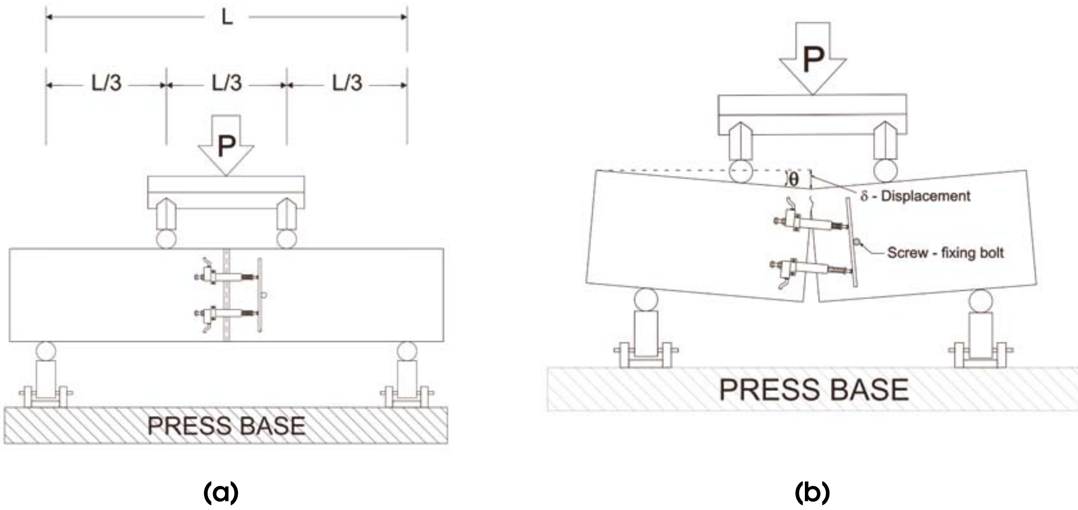
2.4.1 Displacement transducers technique

This technique consisted on employment of displacement transducers attached in the beam sides and placed as those were fixed in one side of beam lateral notch and its respective ends supported on a glass sheet attached to the other side of notch. With the test development and the consequent cracking of beam in notch, the displacement transducers measured the distance between the fixing points of displacement transducers placed in one notch side and the glass sheet attached to the other side. There were employed 2 transducers on each side of beam. One transducer was placed at a distance of approximately 10 mm from the beam base and the other transducer at a distance of approx. 50 mm above the first, being both also positioned at a distance of approx. 30 mm from the notch center.
In Figure 2 it is possible to view the two displacement transducers attached on the beam sides and the glass sheet on which these transducers were leaned. In this figure, there are also viewed the strain gauges used for monitoring of compressive strains, the grid line employed for measuring with digital image processing technique, the metric scale for conversion of measures in digital image from pixels to millimeters, the watch employed to relate the data captured by data acquisition system and the digital image obtained, the tip of displacement transducer used to measure the vertical displacement of beam, the test corbels for load application and the tag identifying the beam side and strain gauges.
As beams had notches in the sides, it was guaranteed that the cracking would occur in the notch and, this way, attaching the transducer to one side of notch and positioning its tip in the other side, with arising of the cracking there was a subsequent separation of the two parts of beam. Therefore, the displacement transducers were able to measure the displacement between these

Figure 2 – Image used for crack width measurement, showing: transducers, strain gauges, grid lines employed to digital image processing, chronometer, metric scale, beam face identification and position of displacement transducers and strain gauges

two parts for the point that they where attached. Knowing the transducers readings (displacement between the two parts of beam after cracking), the position of each transducer and considering the rigid body movement among the two part of beam, it was possible to determine the crack width at the region of the maximum tension stress (beam base), the crack width throughout the entire beam height and the point of beam in which the crack-mouth opening is null. The beam height in which the crack-mouth opening is zero provides, also, an indicative of the neutral axis position. Reminding that the neutral axis position is measured from the beam top.
It is important to emphasize that, during cracking, the beam behave as two rigid blocks which independently separates and each side of cracking are displaced with a certain inclination which is proportional to displacement of the center of its spam. Due to this inclination of beam parts and due to the fact of displacement transducers be attached on the beam sides, the reading performed by the displacement transducer does not correspond to actual crack width in the transducer position (Figure 3).
When there were used displacement transducer attached on beam sides to measure the crack width, these transducers move along with the beam lateral so that these suffer a rotation. The rotation stood by displacement transducers is the same that occurs in the beam, that is, it is displacement function. This causes the transducers to not maintain itself in horizontal position as they should be in order to enable the measuring of crack width at the height in which they are positioned. These transducers rotate as the beam displacement increases so that the values measured by these do not correspond to actual crack width in the height that they are positioned, therefore, being necessary the correction of its readings, in function of beam displacement.

Figure 3. Flexural test scheme on four points of beams (a) test setting; (b) movement of rigid body during the tests.



In Figure 4 it is presented a displacement transducers rotation scheme by reason of the beam displacement.

The crack width on the point where the displacement transducer is placed (OPEN) is determined by knowing the distance between the transducer tip and the crack-mouth face (L_2) and the angle θ, being that the angle θ is function of displacement (δ) and spam (L) of beam, according to equations 1 and 2.

$$OPEN = \left[TR - L_2 \times \left(\frac{1}{\cos\theta} - 1 \right) \right] \times \frac{sen(90 - 2\theta)}{sen(90 + \theta)} \quad (1)$$

Where:

OPEN = crack-mouth opening in the point in which the displacement transducer is fixed, this is the distance that must be determined. (mm)

TR = value measured by the displacement transducer (mm)

L_2 = distance from the tip of displacement transducer on beam to the crack-mouth face (mm)

θ = beam inclination angle based on displacement

$$tg\theta = \frac{\delta}{L/2} \quad (2)$$

Where:

δ = beam displacement (mm)

L = beam spam (mm)

2.4.2 Digital image processing technique

Another procedure used for the crack width measurement during the period of tests was the digital image processing technique, which consists of obtaining measurements through photographic images. This technique was employed by Robins et al. [6], which denominated it as grid method. In this work there was employed this image analysis technique for evaluation of crack width on the two lateral faces of beam.

It was employed a printed line grid (Figure 2) on an adhesive paper which was bonded over the side surface of beam. The lines crossing were the measuring points for evaluation of grid distortions along the test. The vertical distance between the reference points used for the measurements (lines crossing) was 5 mm and the horizontal distance was 30 mm. The grid was glued on the entire lateral height of beam, being excluded only the region where the strain gauges was bonded.

The images were acquired with two SONY brand digital cameras; model DSC V1; with 5 megapixels.

The positioning of cameras during the test can be viewed in Figure 1.

The cameras were positioned on tripod, with the lenses parallel to sides of the beam to be captured, at a distance of approximately 70 cm. The images were captured as follows: a first initial image was acquired before the beginning of test. This first image was the reference image. The capture of the rest of images is initiated right after the crack-mouth arising, that is, when it was observed that the average of displacement measured by displacement transducers was above 0.3 mm. From this displacement value, the images were captured in sequence, with approximately 3 second interval between the shots. The selection of this displacement value for beginning of image capture is associated with the fact that, for displacements below this value, the crack-mouth opening is so little that the image analysis technique does not have accuracy for its measuring. The shots for image capturing were performed by remote control device to avoid the movement of camera during the test. The two remote controllers, one of each camera, were linked in such way that they were simultaneously shot.

At each captured area (two faces of beam) there were positioned two equipments: a metric scale in order to enable that the calibration of image for measuring of crack-mouth openings were performed and a chronometer to allow the relationship of photo with the displacement and load value which were being captured by the data acquisition system while photographing. To enable this synchrony, the data acquisition system and the chronometer were turned on at the same time. Thus, the data acquisition system did register the time of each piece of collected data and the photo chronometer did register the moment of image capturing. In addition, each beam side was identified in the photographed area, and also being identified the displacement transducers and strains gauges used on each side.

An example of image used for crack width measuring is presented in Figure 2, where also is highlighted the strain gauges used for measuring the deformations and the displacement transducers employed for crack-mouth opening monitoring.

The first step of images analysis consisted in the selection of photographs that would be employed for measuring of crack width. There were chosen the beam displacements of 0; 0.5; 1.0; 1.5 and 2 mm for measurement of crack width. Thus, with the data recorded by data acquisition system, there was possible to determine the time of the test in which occurred each one of the analyzed displacements. With this time, there were searched, among the images, which one was correspondent to each time and, consequently, to each displacement. In case of the image corresponding to a certain displacement had not been acquired, it was used the image closer to the time desired and it was searched in the acquisition system data the displacement which was related to such image. Such procedure was carried out for the two images acquired for each face of beam, always using the pair of captured images at the same time for evaluation of crack-mouth opening at a certain displacement.

The selected images were transferred to a drawing program in which were performed the required measurements for determining of spacing between the reference points of image and, consequently, the crack width at each point.

In each image the following measurements were performed, always in pixel.

a) x and y coordinates of each crossing of reference lines, identified by uppercase letters in the grid. These coordinates were manually measured and by means of a computer-based software program of automatic recognition of features in digital images.

In the manual analysis, the selected images were transferred to a drawing program in which were identified the crossing of reference grid lines and determined the coordinates (in pixels) of these crossings. The computer-based program, developed specifically for this job, did perform a scanning over the image to be analyzed, with a mask (or search matrix), which models the feature to be recognized, in case of reference

Figure 4 – Displacement transducers rotation scheme according to beam displacement.

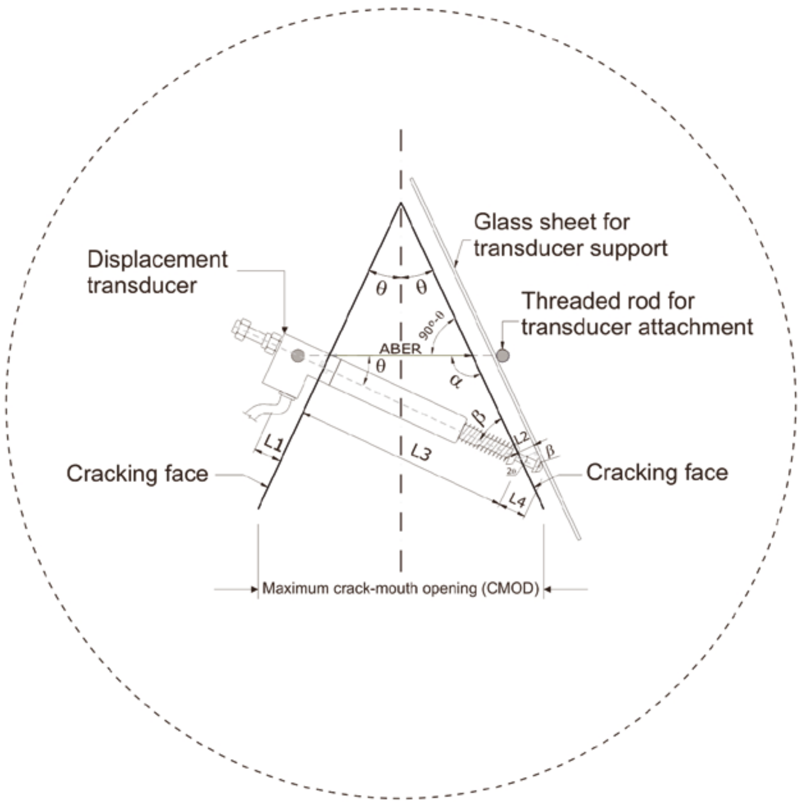
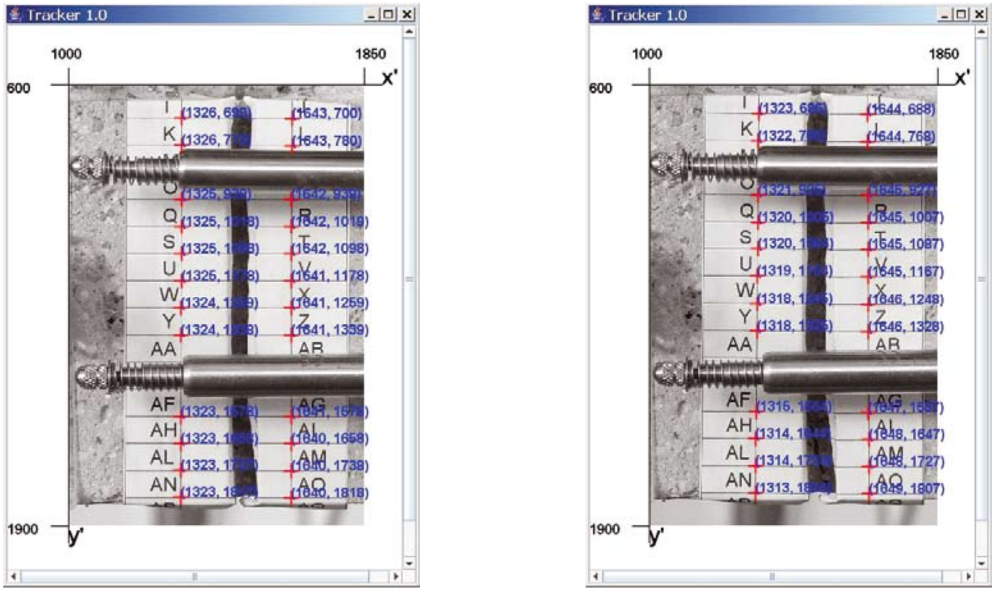


Figure 5 – Images analyzed by computer-based software, with the coordinates identified by the program for each crossing ofgrid lines, for (a) image related to initial displacement (zero) and (b) image related to displacement of 1.5 mm, both from Beam 1.



(a) (b)

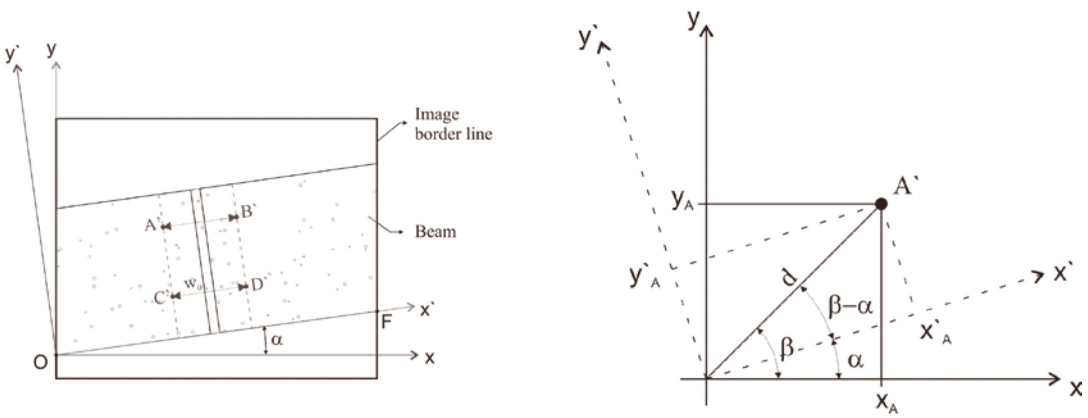
grid lines crossing. With this, the program identified and registered the coordinate values of pixels that fit to the mask, considering certain correlation coefficient. Examples of test images of a beam that had been processed by the program are presented in Figure 5.

b) Y values in the base center and beam top, to determine its height;

c) Y values of lower left corner and lower right corner of beam base, to determine the beam inclination in image, because it was very difficult to avoid a little beam inclination in the image when positioning the camera and the beam;

d) Distance in pixels of a certain distance in millimeters of metric scale to obtain the relation between pixels and millimeters

Figure 6 – (a) Graphic schematization of beam inclined position in photo image and (b) detail of point A



(a) (b)

of image and transform all these measures to the International Metric System;

e) Y value of strain gauges center and displacement transducers for determination of positioning of each one of these equipments at beam height.

f) X value of notch center and displacement transducers tip, to determine the distance (L2) employed in crack-mouth opening correction performed by each displacement transducer.

Known all these parameters measured images, it was possible to determine the crack width of each point of beam in which had a reference point (grid lines crossing). This was made by the difference between the coordinates of each crossing of lines in image correspondent to the analyzed displacement (0,5; 1,0; 1,5 and 2 mm) and the coordinates of each line crossing in the reference image (image corresponding to 0 mm displacement). However, some corrections were necessary to determine the actual crack width in which the coordinates were measured, taking into account the inclination of each side of beam after it was cracked.

It is necessary, firstly, correct all the coordinates measured in the reference grid lines crossing. This is necessary because, when positioning the photographic camera, many times it is not guaranteed its flawless leveling and due to this, the beam image on photograph can be a little tilted. In case of these corrections are not carried out, the distance measurements between the grid points will not correspond to the actual crack-mouth opening, but the projection of this opening.

This inclination in the beam on image can be schemed, according to Figure 6(a) and the positioning of a point referring to crossing of lines in the image axis and to beam is detailed in Figure 6(b).

In Figures 6(a) and 6(b) it can be assumed that:

x and y = image axis

x' and y' = beam axis

α = angle between the image axis and the beam axis.

β = angle between the diagonal (d) of point A and the image axis.

To know α it is necessary to determine x and y coordinates of beam base extremes, points O and F in Figure 6(a). So:

$$\tan\alpha = \frac{|y_F - y_O|}{|x_F - x_O|} \quad (3)$$

To determine β it is employed the coordinates of the point that is being corrected, in this example, the coordinates of point A.

$$\tan\beta = \frac{y_A}{x_A} \quad (4)$$

The diagonal d is determined by the following Equation:

$$d = \sqrt{(x_A)^2 + (y_A)^2} \quad (5)$$

The corrected coordinates of point A will be obtained by Equations 6 and 7.

To correct the coordinates of the rest of points you must repeat these

$$x'_A = d \times \cos(\beta - \alpha) \quad (6)$$

$$y'_A = d \times sen(\beta - \alpha) \quad (7)$$

calculations, from the coordinates relative to each point on the image.

After obtaining the corrected coordinates of all points referent to grid lines crossings, you must proceed to calculations for determination of crack width. In this step, it must be reminded that when cracked, the beam splits into two blocks, united by a plastic hinge (rigid body motion) according to Figure 3, being that the inclination of each side of beam (θ) is proportional to beam displacement (δ). Due to this movement, distancing of the two beam parts occurs, subsequently, the distancing between the grid points positioned at each side of crack-mouth and the rotation of each one of the parts. This effect is schematized in Figure 7, in which presents the positioning of points in the reference grid before the cracking (Figure 7(a)) and the positioning of points in the reference grid after the cracking (Figure 7(b)).

From Figure 7(a) it is defined:

w_0 = distance between the points C' e D'

$$w_0 = |x'_D - x'_C| \quad (8)$$

Where:

x'_C e x'_D are the corrected x coordinates of the points C and D in the first image, before cracking.

Considering the schematized movement in Figure 7(b) it is observed that the crack-mouth opening at the points C" and D" level corresponds to the distance w between these points, and not the distance d_3, and for this reason it is not possible to determine the crack width doing only the differenced between points C" and D" coordinates. To determine the crack width, you must know the distance w.

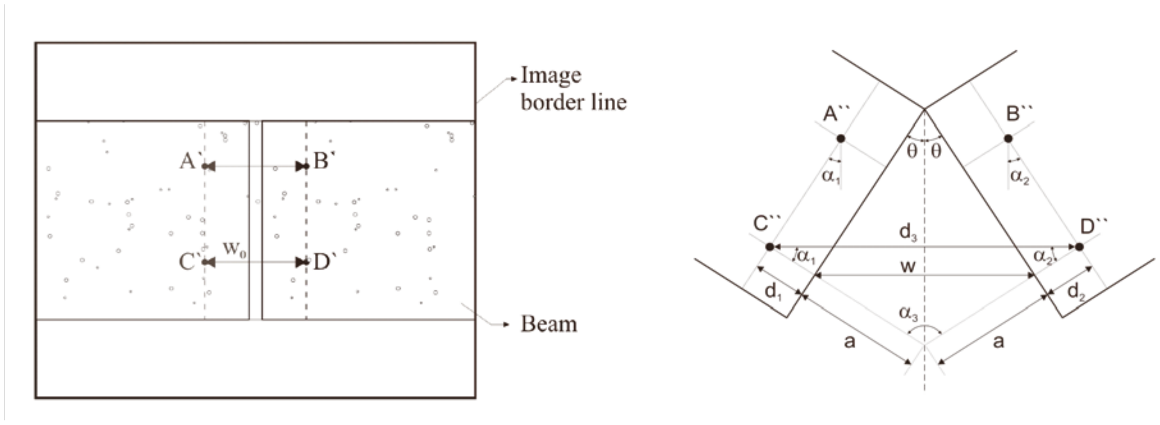
From the points C" and D" coordinates in the second image (image of the beam already cracked), it is possible to obtain the distance d_3 between them.

$$d_3 = \sqrt{(x''_C - x''_D)^2 + (y''_C - y''_D)^2} \quad (9)$$

It is also possible to determine the angles α_1, α_2 e α_3, according to Equations 10, 11, 12.

$$\tan\alpha_1 = \frac{|x''_A - x''_C|}{|y''_A - y''_C|} \quad (10)$$

Figure 7 – Positioning of points in reference grid employed for measurement of crack width (a) before cracking; (b) after cracking



$$\tan\alpha_2 = \frac{\left|x''_B - x''_D\right|}{\left|y''_B - y''_D\right|} \quad (11)$$

$$\alpha_3 = 180 - \alpha_1 - \alpha_2 \quad (12)$$

From Figures 7(a) and 7(b) it is possible to deduce:

$$w_0 = d_1 + d_2 \quad (13)$$

Applying the sine law in the triangle formed by angles α_1, α_2 e α_3, it is possible to determine the side 'a' of this triangle.

$$a = \left[\frac{d_3}{2sen\alpha_3}\left(sen\alpha_1 + sen\alpha_2\right)\right] - \frac{w_0}{2} \quad (14)$$

Applying the cosine law in the triangle formed by sides 'a', 'a' and 'w', it is possible to determine the crack width (w) related to the height of points C" and D".

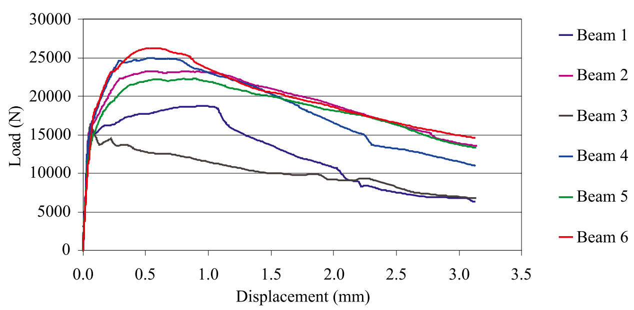
$$w = \sqrt{2a^2 \times \left(1 - \cos\alpha_3\right)} \quad (15)$$

In order to determine the crack width referent to the rest of grid points, the calculations presented in Equations 8-15 must be repeated. At the end, being known the actual crack width at each beam point in which the coordinates of line crossings for each face of beam were measured and taking into consideration the rigid body movement, there is determined the straight equation that better adjusts to points in the crack-mouth opening by distance from the point to the beam top, for the two beam faces. With the simple arithmetic average of the two adjusted straight lines, it is possible to determine the position on the point of beam in which the crack-mouth opening is zero, considering this the neutral axis position, and the crack-mouth opening in the region of maximum tension stress (base), for each displacement level analyzed. Reminding that in this work, the value for neutral axis position varies from zero to 50 mm counting from the beam top.

3. Results and discussions

In Figure 8 the load per displacement curves are presented of 6

Figure 8 – Load-displacement curve of 6 tested beams



tested beams for assessment of crack width monitoring and neutral axis position techniques.

The difference of behavior between the loads-displacement curves verified in Figure 8 is typical in steel fiber reinforced concrete beams test results. As demonstrated by Gava et al. [8] this difference of behavior is normally assigned to the quantity of fibers present in beam fracture section, as well as the positioning, localization and apparent length of these fibers.

With the compressive strain data measured by strain gauges for each position, it was possible to obtain the straight lines relating such parameters, and considering that the compressive strains are zero in neutral axis, with these straight lines it was presumed the neutral axis position for each displacement analyzed. Similar procedure was carried out with the crack-mouth opening data measured by displacement transducers and through digital image processing analysis, being that for these two last procedures, it was possible to determine not only the neutral axis position, but also the crack-mouth opening on the maximum tension stress region (beam base). It is convenient to remind that the strain and crack width monitoring was performed in the two faces of beam and the presented results correspond to average of measured values at each face.

As detailed in the methodology, the data obtained with displacement transducers employed in monitoring of crack-mouth opening can be corrected in relation to inclination of transducers during the test development. In order to evaluate if this data correction of transducers would produce significant differences between the neutral axis position and the maximum crack width values, it was made a comparative study with data of the 6 tested beams. In Table 1, the neutral axis position and crack width values determined with and without data correction of transducers are presented, for each displacement and beam analyzed and for relative error between these two measurement forms.

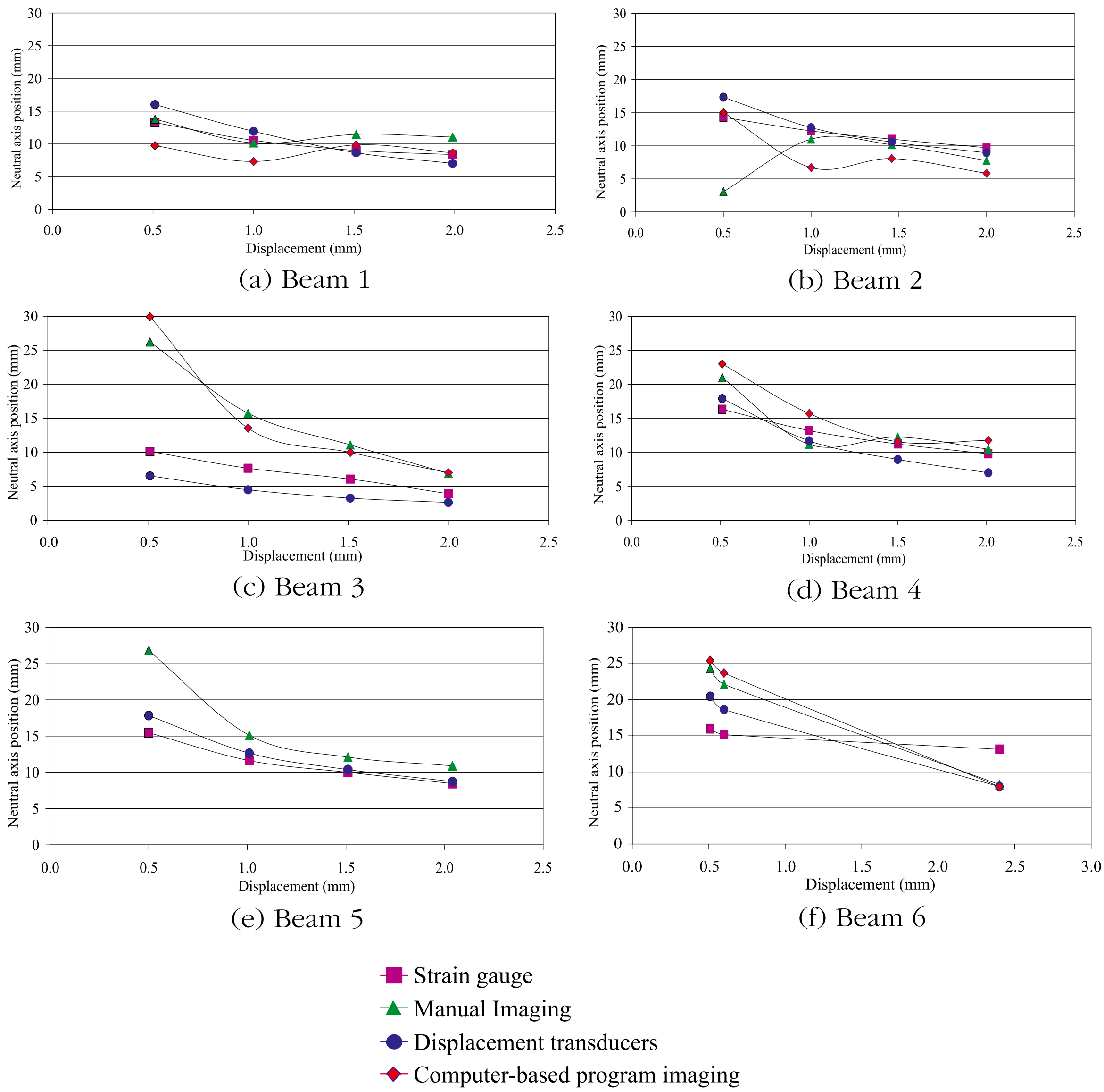
The Table 1 data reveals that there is difference between neutral axis and crack width values obtained from displacement transducers data which had the values corrected or not in relation to the inclination of transducer during the test. The relative error among the two transducer data analysis ways indicates that the neutral axis position values are those which suffer major alterations. It is possible to verify also that insofar as the beam displacement increases, the relative error between the transducers data corrected or not also increases. This error increasing in relation to the beam displacement increasing was already expected, once the transducers data correction is made based on inclination that the transducer suffers during the test due to the rigid body movement of beam. Thus, increasing the beam displacement also increases the transducer inclination. Based on these results, it was decided by the necessity of correction, in the light of transducers inclination during the test, from all displacement transducers data used to measure crack width in this work.

Table 1 – Neutral axis and crack width values determined from displacement transducers data

Beam	Displacement (mm)	Neutral axis position (mm)			Max. crack-mouth opening displacement - CMOD		
		Transducers w/o correction	Transducers corrected	Relative error (%)	Transducer w/o correction	Transducers corrected	Relative Error (%)
1	0,51	15,89600	16,00950	-0,71	0,53159	0,53093	0,12
	1,00	11,68750	11,91000	-1,90	1,09841	1,09582	0,24
	1,51	8,32675	8,64445	-3,82	1,81693	1,81086	0,33
	1,99	6,60270	7,01000	-6,17	2,52078	2,51005	0,43
2	0,49	17,24300	17,34300	-0,58	0,53383	0,53318	0,12
	1,00	12,55500	12,74770	-1,53	1,19359	1,19090	0,23
	1,46	10,27430	10,55685	-2,75	1,80807	1,80215	0,33
	2,02	8,55830	8,95115	-4,59	2,52706	2,51558	0,45
3	0,51	6,40855	6,54295	-2,10	0,47825	0,47754	0,15
	1,00	4,24960	4,49170	-5,70	1,05938	1,05655	0,27
	1,51	2,90355	3,26025	-12,28	1,65136	1,64487	0,39
	2,00	2,16045	2,62930	-21,70	2,20446	2,19301	0,52
4	0,51	17,80250	17,91450	-0,63	0,49636	0,49573	0,13
	1,00	11,50950	11,70195	-1,67	1,10887	1,10656	0,21
	1,50	8,65995	8,96690	-3,54	1,78143	1,77558	0,33
	2,01	6,60735	7,01300	-6,14	2,46425	2,45361	0,43
5	0,50	17,69950	17,83300	-0,75	0,45110	0,45035	0,17
	1,01	12,39180	12,63625	-1,97	1,09495	1,09181	0,29
	1,51	10,01900	10,37535	-3,56	1,72028	1,71317	0,41
	2,04	8,24410	8,71910	-5,76	2,38836	2,37528	0,55
6	0,51	20,32050	20,44550	-0,62	0,48587	0,48513	0,15
	0,60	18,47900	18,62550	-0,79	0,59101	0,58869	0,39
	2,40	7,40655	7,95105	-7,35	2,86455	2,84743	0,60

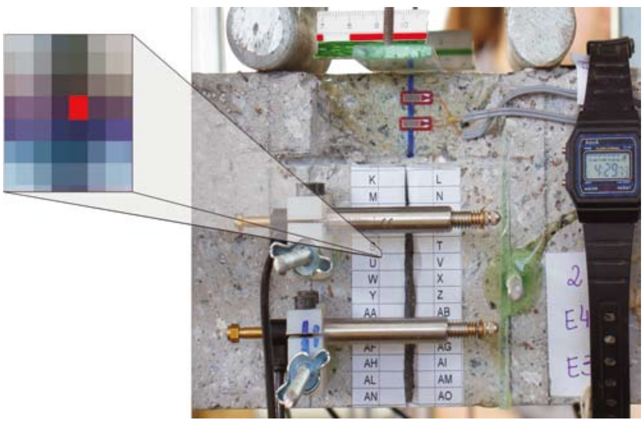
In Figures 9(a) to 9(f), there are presented the relations between neutral axis position and displacement obtained through three methods: strain gauges, displacement transducers and image analysis. The digital images were analyzed in two manners: manually and with the computer-based program.
From Figures 9(a) to 9(f) it is possible to evidence that the neutral axis position values determined by data obtained from manually processed image analysis are in some cases very different from those determined by data from strain gauges and displacement transducers. It would be convenient to draw the attention to data of beams 1, 2 and 4 images, in which it was not observed the neutral axis trend to get closer to beam top with the increasing of displacement, since that in these beams some neutral axis position values increased with the displacement increasing. The neutral axis position values determined by strain gauges and displacement transducers data did indicate the expected trend, that is, decreasing its value insofar as the beam displacement increases.
It was observed in Figures 9(a) to 9(f) that the major errors in neutral axis position measurements by image analysis method do occur in the minor displacement values. This difference is assured to the small crack-mouth opening values measured. At some points measured in images, the crack width values are too close to measurement precision, that is, too close to a pixel. It is important to emphasize that in all the images analyzed for determination of

Figure 9 – Neutral axis position based on the displacement determined by the three equipments: strain gauge, digital images and displacement transducers



crack width and neutral axis position, 1 pixel corresponds to 0.065 mm at maximum. Thus, at points where the crack-mouth opening was below 0.065 mm it was not possible to measure by the image analysis technique.
In manual processing of digital images there was a difficulty to choose the pixel correspondent to grid lines crossing, as shown in Figure 10. Besides that, with the analysis of several images, it was perceived that the choice of pixel to be measured was, many times, influenced by the person who did the analysis and, sometimes, the coordinate values measured by a same person in the same image were different. Such observations indicated that this image analysis process was being far influenced by the person who did carry out it.
With employment of computer-based program it was not possible to identify the coordinates of all points of images. In mostly cases, the points near to lower and upper edges of the analyzed image were not identified, therefore making impracticable the image analysis of Beam 5 by this method. In the automatic resource recognition program there were analyzed 48 images, which resulted in 942 points and 1884 coordinates identified. From these data, it was verified that 77,1% of cases the coordinates measured by the program were equal to the manually measured coordinates, in 21,0% the difference between the coordinates evaluated by each system was only 1 pixel, and in only 1,9% this difference was 2 pixels, not being checked differences above 2 pixels.
Analyzing the Figures 9(a) to 9(f) it can be sensed some differences between the neutral axis values determined by analysis data from manual images and by the program, being that the major difference has occurred at the point referent to 0,5 mm displacement of Beam 2.
Analyzing the data referent to coordinates of grid lines crossing points of this beam, it was observed that the coordinates measured by these two methods are, in mostly cases, equal, being that at only two points the difference between the coordinates measured by each method is equivalent to 2. With these data, a simulation was performed in which the changing of only 1 pixel was made to only one coordinate of analyzed points in a certain image and the neutral axis position was then calculated. It was observed that the 1 pixel error on coordinates x or y of the points nearest to beam top, normally at a distance below 55 mm, that is, on the points where the crack-mouth opening is very small, changes significantly the neutral axis position. Changes in the coordinates of points far from top, that is, where the crack-mouth opening is larger, do not cause change in neutral axis position. This simulation was carried out with the coordinates data obtained from analysis of the rest of beams and there were verified that changes on x coordinates did influenced the neutral axis position more than the changes on y coordinate.
Another item to be analyzed is the crack width, which can be determined from displacement transducers data and from digital image processing. The maximum crack width values for each displacement value for Beams 1 to 6 are presented in Figures 11(a) to 11(f).
Analyzing the Figures 11(a) to 11(f) it is observed few differences in crack width determined by the two measurement systems: displacement transducers and image analysis, including both ways to perform the image analysis, either manually or by computer-based program.
Comparing the Figures 9(a) to 9(f) with Figures 11(a) to 11(f) it is observed that even having differences in the neutral axis values determined by the several measurement systems, there are no differenced in the maximum crack width determined from the same data. This leads to conclude that the maximum crack width is almost not influenced by the variation in straight linear coefficient (neutral axis position value) used for its determination. This occurs because the maximum crack width depends on greater values of crack width, this is, from those that are nearest to beam base, while the values of neutral axis position (straight linear coefficient) are most influenced by the measures performed in the points nearest to beam top. For these reasons, measurement errors of coordinates of points in image analysis, as previously shown, cause major changes in the neutral axis position and minor influence in the maximum crack width.

Figure 10 – Example of image used for crack-mouth opening indicating the difficult to select the pixel corresponding to the grid lines crossing



4. Conclusions

In face of the results found it was verified that the three techniques evaluated in this assay: strain gauges, displacement transducers and digital image processing, demonstrated to be variable for measurement of neutral axis position and crack width during the development of the steel fiber reinforced concrete beams flexural test. However, some considerations should be made.
The values encountered for neutral axis position determined from strain gauges and displacement transducers data were more coherent than those obtained with image analysis data. The measurement of neutral axis by image analysis technique is very influenced by little variations in coordinates of measuring points. With respect to crack width values, the results obtained from displacement transducers and digital image processing were very similar.
In order to choose the best technique for measurement of crack width and depth of neutral axis, you must take into consideration not only the accuracy of the measurement system, but also the availability of equipment or financial resources for purchasing it.
Strain gauges are expensive material and in the way that they were employed in this assay, such equipment cannot be reused,

because they were led to its rupture. Displacement transducers are not very expensive equipment, when compared to all other equipments employed in the beam flexural test, such as the universal test machine and the load cell. The investment in such displacement transducers becomes interesting, because these equipments are employed for several tests at a structures and civil construction materials laboratory. However, its using requires a data acquisition system and if the test lab does not have it, the investment will be far more costly.
The digital image processing showed to be a relative cheap technique, because the digital camera employed in this assay, with 5 megapixels resolution, is a simple and available equipment, since the majority of digital cameras existent in the market already have this resolution required for the test. In event of the laboratory do no have a data acquisition system and not even resources for its purchasing, becoming unable the employment of strain gauges and displacement transducers, the employment of digital image processing technique for measurement of crack width would become interesting.

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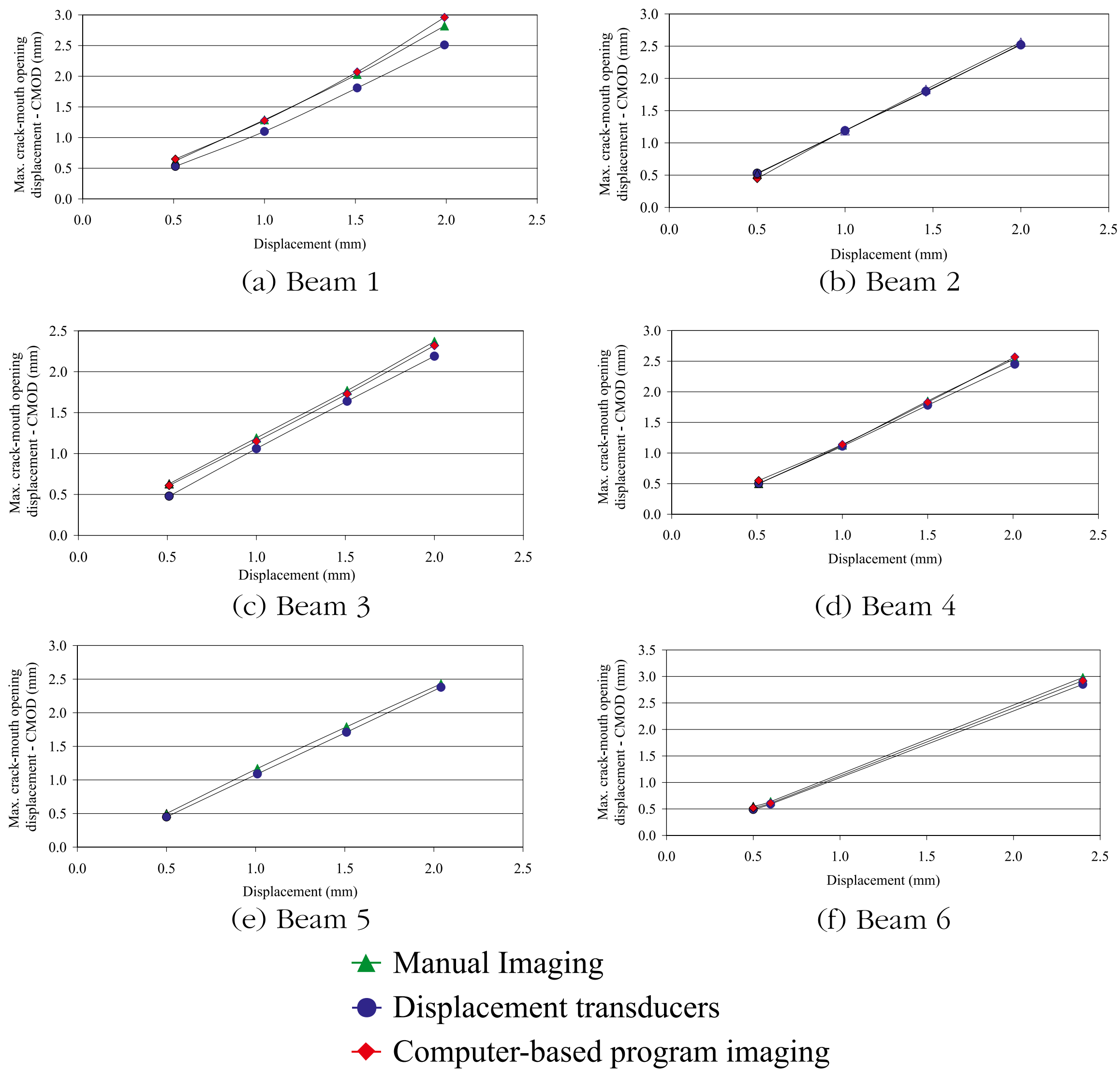
Figure 11 – Maximum crack width based on displacement determined by data obtained from the image analysis performed manually and performed with the computer-based program and with the data from displacement transducers



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