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Crack Propagation Observation Using Digital Image Correlation (DIC) on Oil Palm Shell (OPS) Reinforced Concrete Beam

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Abstract: In terms of disaster risk management, crack opening and the behaviour of structural elements should be predicted to prevent severe risk after the failure. To do so, the structure responses, and crack propagation phenomena of concrete structural elements should be understood. Opening, re-closing, or re-opening of cracks in concrete may occur under some circumstances. Capturing the behaviour along the test, sometimes, becomes a problem. Measurement tools should be detached to prevent damage as the sample reaches failure point. A set of contactless devices, called Digital Image Correlation (DIC), has been developed in the Laboratory of Structural and Material Universitas Indonesia. In this research, experimental on Oil Palm Shell (OPS) concrete beam with 19 MPa of fc’, was conducted under four-point loading in the laboratory. OPS is a solid by-product obtained from palm oil production. This experiment uses a 300 x 15 x 250 cm3 beam under a semi-cyclic loading protocol. Load vs deflection, strain, and cracking behaviour are obtained by using the DIC system as its equipment. The conventional measurement (dial gauge) results were compared to the DIC results. Measurement from both tools have similar values. Also, this DIC system can capture deflection and measure crack opening evolution along the test.

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Keywords: oil palm shell; digital image correlation; reinforced concrete beam

1. Introduction

In terms of disaster risk management, the condition of security, comfort, and safety of public buildings should be assured to prevent negative impacts after catastrophic failure. To control this condition, as in regulations, buildings in Indonesia must be certified, known as Functional Eligibility Certificate, so called Sertifikat Laik Fungsi - SLF. SLF is an official certificate issued by the government for a building that has completed its construction period. This document can be delivered if the building is following the technical feasibility requirements in accordance with its function and IMB (Izin Mendirikan Bangunan). Furthermore, one way to verify a building’s function is an in-situ loading test following SNI 2847: 2019 [1]. In a real case of a simple building in-situ loading test, structural responses are sometimes difficult to be captured and be observed comprehensively.

On the other hand, to prevent severe risks of the structure’s failure after the disaster, the entire behaviour of structural elements should be predicted. Responses to certain conditions, such as seismic, can be used to understand building capacity besides other gravity loads. Further on specific phenomena, such as crack propagation, it also plays an important role. Small cracks can propagate and weaken the part of the solid element, so that, they can trigger large failures under some circumstances, such as degradation of concrete and large damage of Reinforced Concrete (RC) buildings [2], [3]. Furthermore, when cracks are able to be predicted, service limit states can be obtained, so, the service of the building can also be limited to anticipate any possible problems. The basic thing to do to be able to predict, is to understand the structure responses, and crack propagation phenomena of concrete. The necessity of studying the real phenomena can be fulfilled by using powerful equipment to observe experimental study in the laboratory or in situ.

These days, some measurement tools to be used in the laboratory to capture and record the structure responses exist. Taking a simple case of RC beam under a four-point loading application, mid-span deflection and crack propagation are the two interesting pieces of information to obtain. Dial gauge and LVDT (Linear Variable Displacement Transducer) utilization are the most preferable to measure its deflection, specifically under its mid-span. Moreover, strain measurement uses strain gauges. It must be glued to the preferred area of observation. Only the area that is attached by this equipment can be captured. In fact, as a crack propagates passing the strain gauge, it will be detached from the sample, and the measurement will be stopped. Also, the strain gauge does not work well when it is subjected to compression.

A system called Digital Image Correlation (DIC) has been developed since the 1980s. Created firstly to learn the displacement field evolution, this technique has been developed to observe crack propagations of concrete in the domain of mechanics. This system is referred to as a contactless method of measurement. It captures photos in digital format and carries out the analysis to obtain the movement, displacement, etc. The study of the behaviour after the failure (post-peak) is achievable, including opening, re-closing, or re-opening of cracks [4]–[6].

In this research, an experimental study on RC Beam using Oil Palm Shell (OPS) concrete is presented. OPS as a solid by-product obtained from palm oil production, has been studied in the laboratory since 2016 [2], [7]–[10]. Using the previous concrete mix design, OPS concrete was casted as RC bean with 300 cm of length, 15 cm of width, and 25 cm of height. By taking a simply supported Reinforced Concrete (RC) beam with a 270 cm span from support to support, the beam was subjected to a four-point loading. The DIC system was utilized to capture the beam's responses with a semi-cyclic loading protocol. This system was applied to observe, and capture the deflection, strain, and cracking behaviour along the test. Besides, conventional measurement, such as LVDT is used, to be compared to the results of DIC. Experimental results show both the DIC system and conventional LVDT measurement have similar values. A contactless DIC system developed in the laboratory is powerful in capturing its deflection and its crack propagations.

2. Experiments Using Digital Image Correlation (DIC)

2.1. Material of Reinforced Concrete (RC)

OPS concrete with 21 MPa of compressive strength using the following previous mix design. The complete data of concrete and steel bar materials used are presented in Table 1 below. The compressive strength tests of the concrete samples were done according to National Standard SNI 03-1974-2011 [11], whilst the tensile strength test of the steel bar was tested following SNI 07-2529-1991 [12].

Tabel 1. Mechanical properties of reinforced concrete

Mechanical Properties	Values
OPS concrete compressive strength	21,03 ± 0,12 MPa
Steel reinforcement bar	
Yield tensile strength	419,28 MPa
Ultimate tensile strength	568,60 MPa

2.2. Detail of Reinforced Concrete Beam

The configuration and detail of the RC beam are presented in Figures 1 and 2.

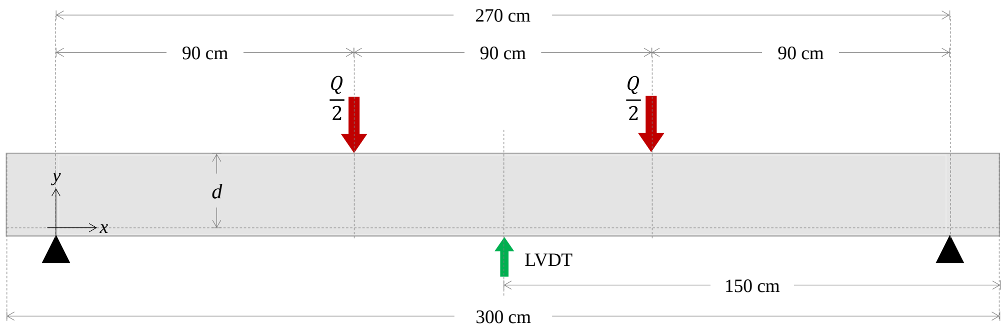


Figure 1. Dimension of RC beam and the position of LVDT and loading application

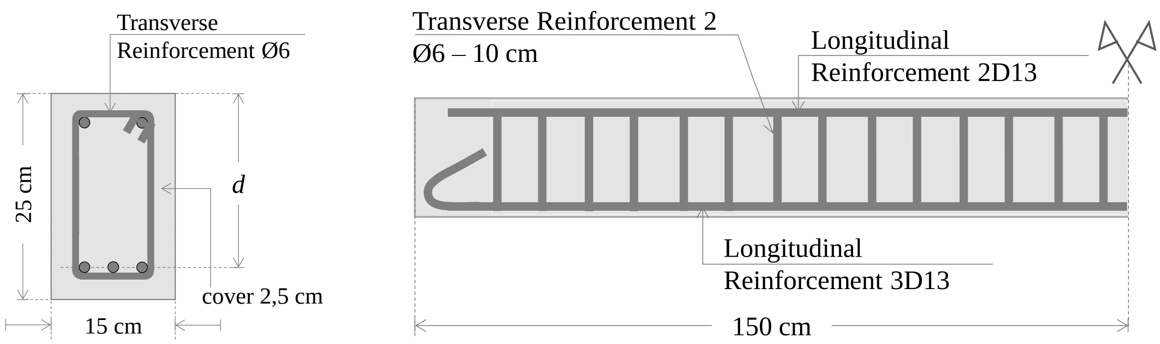


Figure 2. Detail of RC beam section

2.3. Loading Protocol

Experimental loading was done manually using a hydraulic jack with a maximum capacity of 20 tons. It was done following the semi-cyclic loading protocol as described in Figure 3 below. When the load is increasing, the step of loading is maintained at 0,2 tonf per step whilst for the unloading, it was maintained at 1 kg tonf f, and for the last 1 tonf (for the 1st cycle) or 2 tonf (for the other cycle), it was maintained at 0,2 tonf per step. In the fifth cycle, the sample was only subjected to 8,25 tonf, following the maximum capacity of the beam.

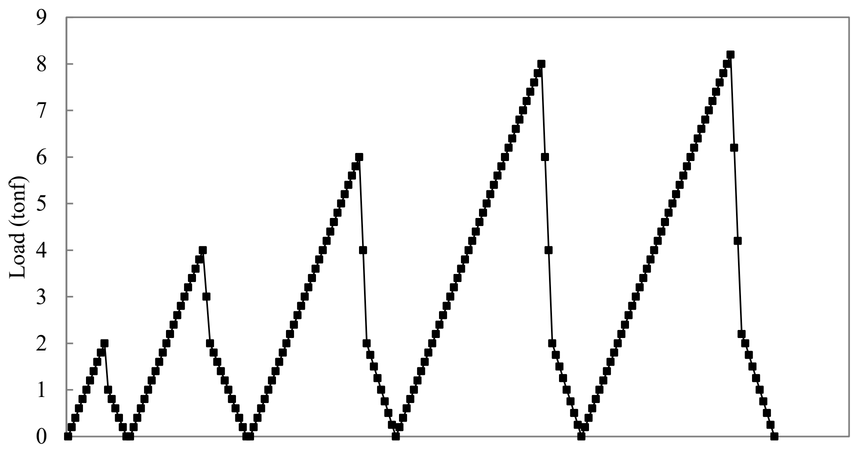


Figure 3. Semi-Cyclic Loading protocol

2.4. Digital Image Correlation (DIC)

Figure 4 shows the schema of DIC application in the laboratory (seen from above) while Figure 5 shows the speckle pattern on the surface of RC beam. The digital camera was set up in front of the mid-span of the sample. it must be ensured that the entire sample can be captured (end to end). A dial gauge, type of LVDT was installed under the mid-span of the beam (see Figure 1, green arrow). The loading application was done manually using a hydraulic jack with 20 tons of maximum capacity. The hydraulic jack should be connected to the acquisition system and camera. Lighting can be used to maximize contrast between the speckle pattern and the white background of the beam.

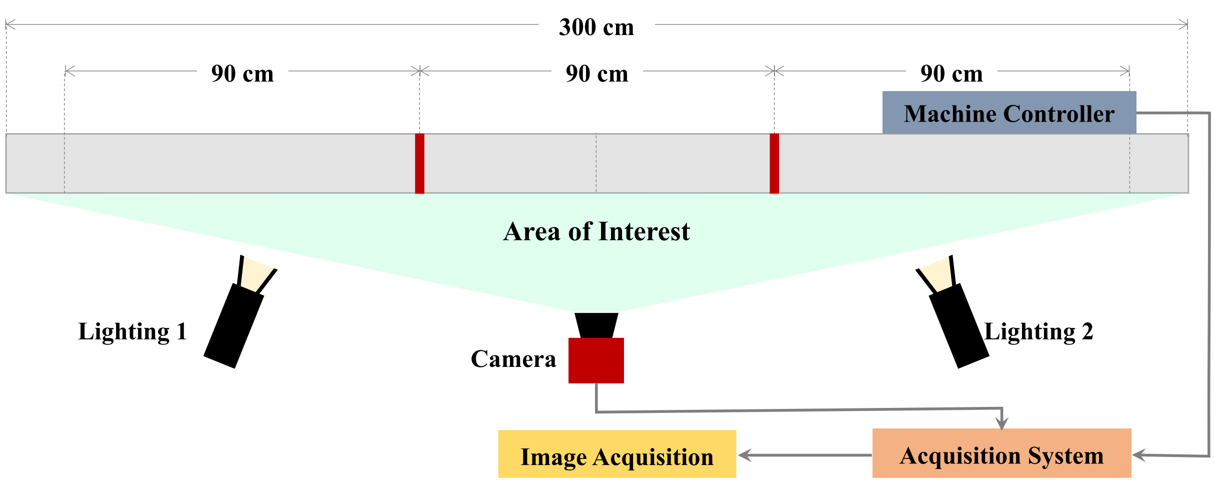


Figure 4. Plan of Application of Digital Image Correlation Technique in laboratory

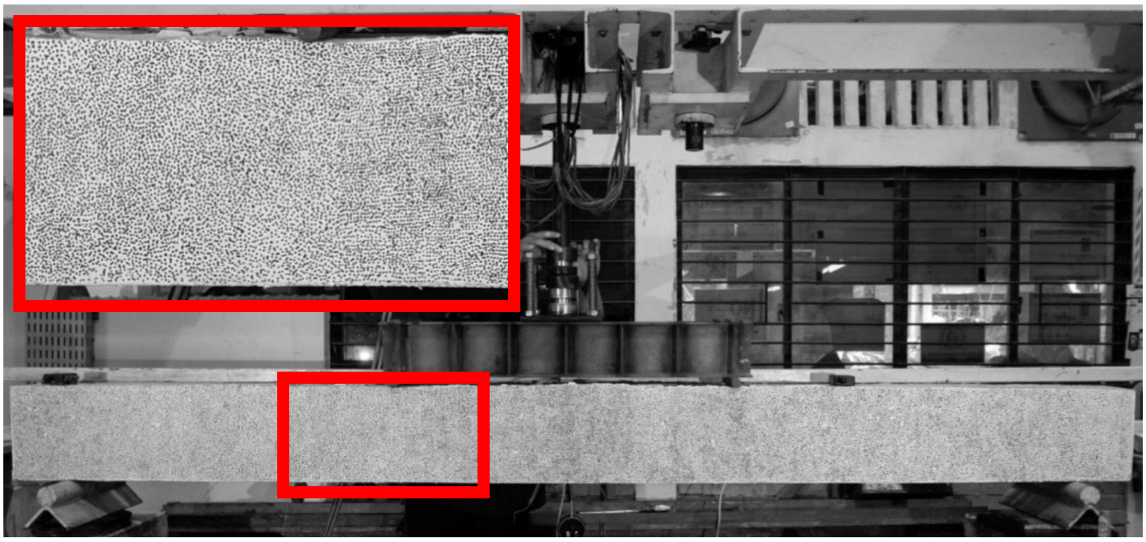


Figure 5. Photo from the camera used in the DIC system. (a) entire sample. (b) speckle pattern

Figure 5 shows the application of the speckle pattern on the beam. This pattern must be applied randomly, so that it is spread sufficiently dense but not forming regular pattern. It should be ensured that the pattern is clear and does not fade following previous research [4], [13], [14]. The speckle pattern plays important role in the post-processing, such as distinguishing every part of the specimen surface, so that the movement of each point (dots) can be traced to obtain displacement.

A camera (Fujifilm XA-5) was utilised to capture photos during the test. The first photo will be used as the initial condition of the sample. The camera was set to take a grayscale picture with a speed of 3 fps (frames per second). To make the photo taken uniformly (in term of proportion and position of each element in the picture) and clear (not blurred), a tripod was used to set the camera stand firmly on the floor. The camera must be arranged appropriately so the lens position is at the same level as the area of interest of the beam to avoid distorted image. Also, to minimize the vibration of the camera, a remote shutter was used. Synchronisation of the force application from machine and the photos in DIC system should be guaranteed by assuring the connection of the machine and the camera. In the post-processing analysis, synchronisation at the exact timing is the key for the results. As the machine load the sample, the camera captured the movement of speckle on the surface of the sample. PS concrete with 21 MPa of compressive strength using the following previous mix design. The complete data of concrete and steel bar materials used are presented in Table 1 below. The compressive strength tests of the concrete samples were done according to National Standard

3. Results and Analysis

3.1. Load-Displacement responses

Figures 6 and 7 show force and displacement in its vertical direction (mid-span of the beam) from the DIC (contactless method) and LVDT (conventional method). From these curves, the DIC results have, more or less, the same values as the ones from LVDT. For some parts, DIC has better results than the ones from LVDT, especially during the unloading in the third cycle (Figure 7 (c)). During the unloading phase, control of the hydraulic jack was sometimes difficult. Also, the LVDT spring response is delayed in following below surface of beam at some cycles. However, the DIC system can capture the movement smoothly. So, the DIC technique can capture the displacement as well as the conservative method, in this case, LVDT.

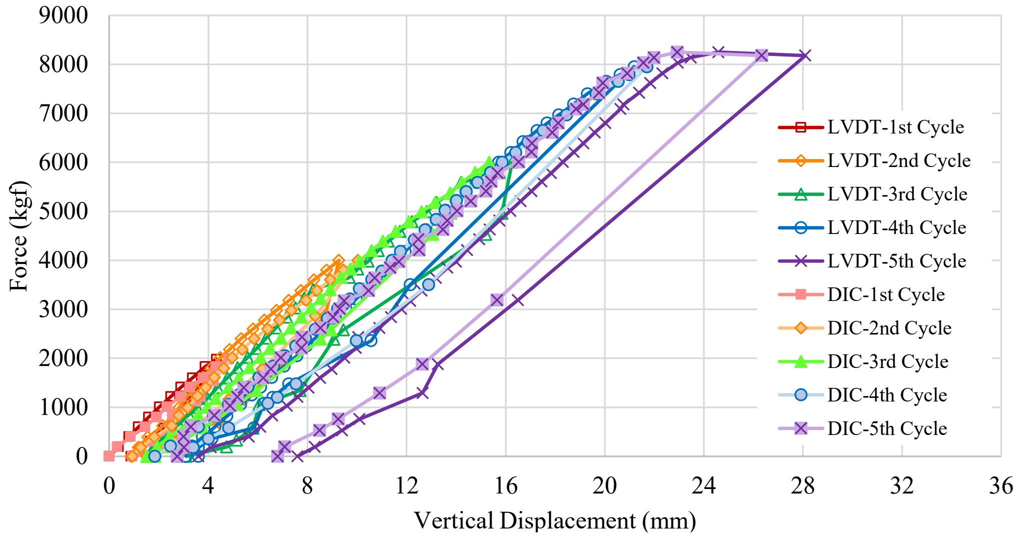
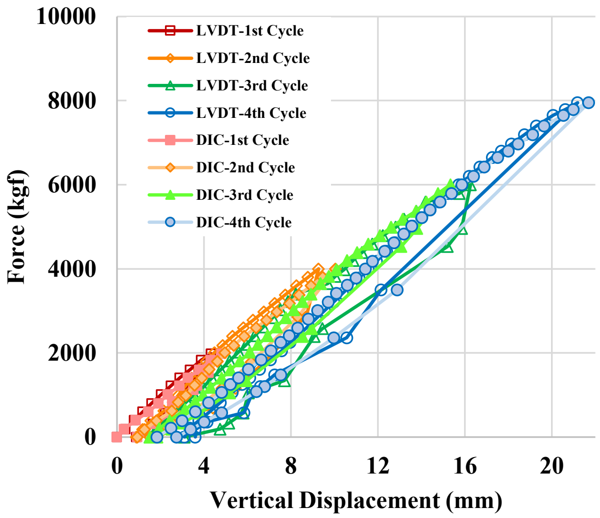
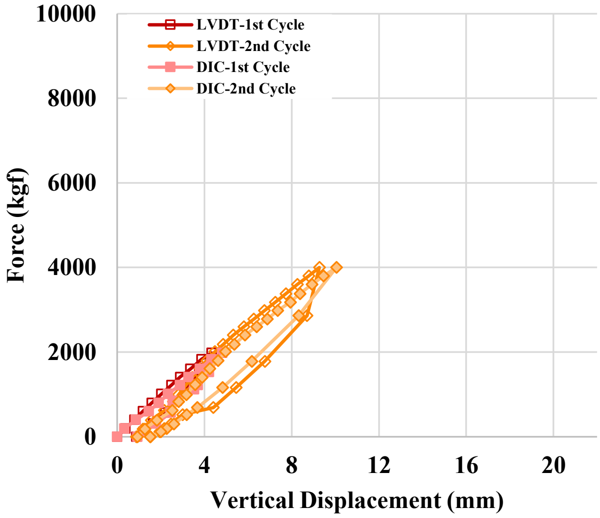


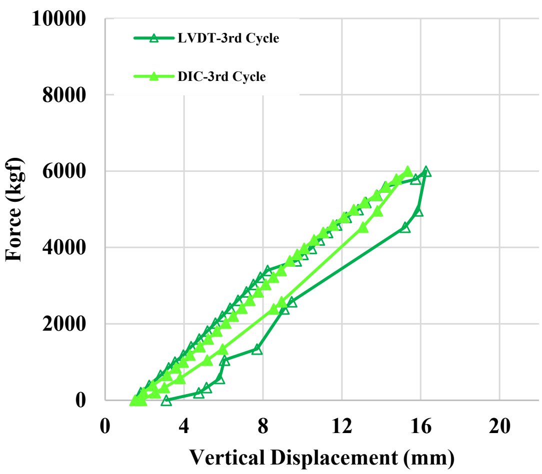
Figure 6. Force vs Vertical Displacement for all cycles



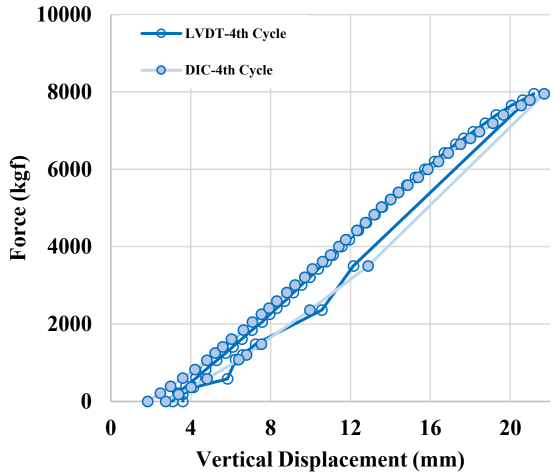
(a) The first four cycles - LVDT and DIC.



(b) The first and the second cycle - LVDT and DIC.



(c) The third cycle - LVDT and DIC.



(d) The fourth cycle - LVDT and DIC.

Figure 7. Force vs Vertical Displacement for the first 3 cycles

3.2. Crack propagation

Discussion of the crack propagation will be focused on the first and the second cycle. Regarding force-vertical displacement in Figures 6 and 7, the first and the second cycle are still in the elastic region. So, during these 2 first cycles, crack opening and re-closing occurred, it was captured by the DIC. In the following, this crack propagation is discussed. Regarding the 4-point bending load, Area C-D (see Figure 1) is considered pure bending area, while area A-C and D-B are considered as the area where shear internal force presents. This condition is chosen as the load is larger than the beam's self-weight.

In the first cycle, in 1990 kgf, the crack opening of concrete can be seen in Figure 8. This image presents the strain field in the major direction that was obtained. The strain field is only used to identify the position of cracks along the loading step. To simplify the figure, images are chosen for each 700-800 kgf of loading step. When force reaches 1010 kgf, small cracks started to appear and propagated vertically. Some noises of the strain field occurred, specifically at the two ends of the beam. It may be the effect of the quality of images from the camera.

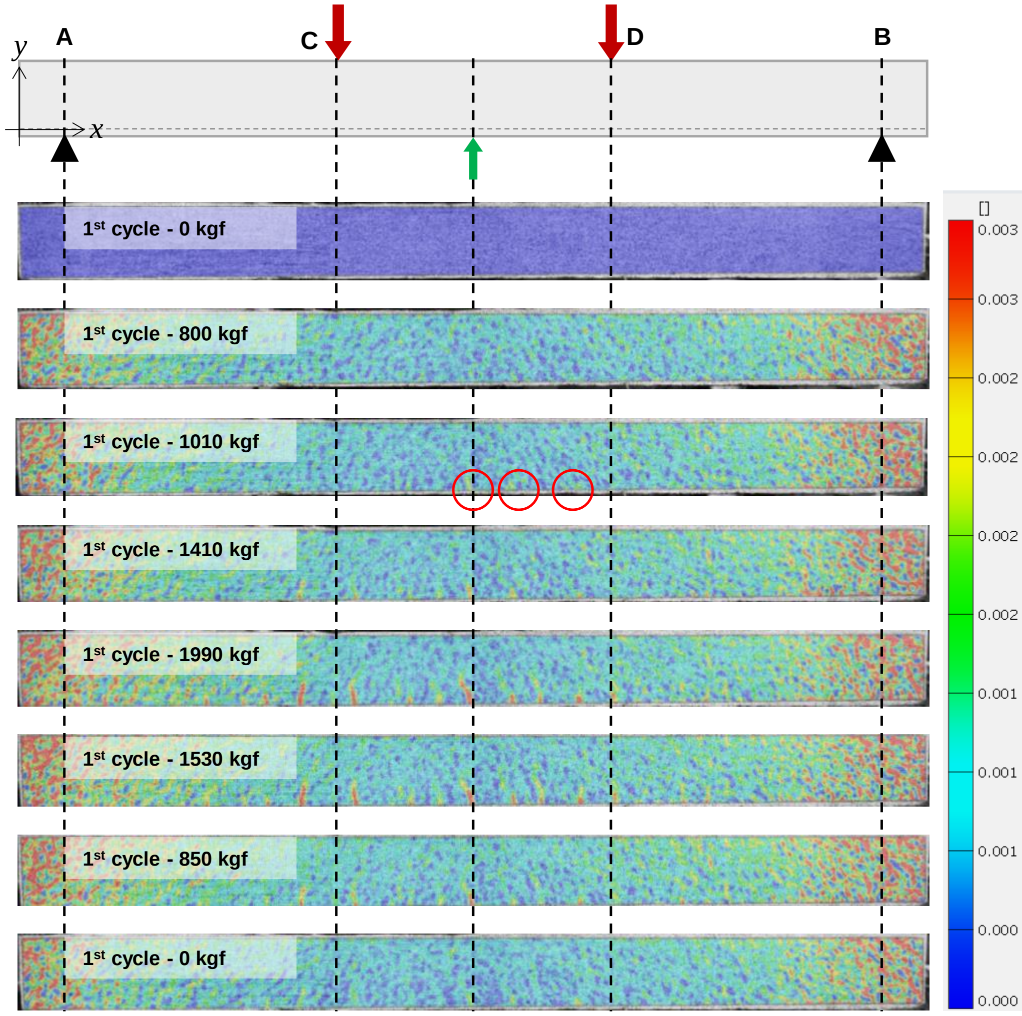


Figure 8. Experimental results using DIC for the 1st cycle: strain field in major direction (ε_{11})

In this cycle, the strain was spread along the observation area. It was due to the distribution of the force when force was applied. At 800 kgf, there was no localized crack yet. This condition more or less follows the theory of smeared cracks on concrete in the elastic region [15], [16]. At 1010 kgf (±1 ton), the first localized cracks appeared in the area C-D. Three red circles show the lines which are considered cracks, starting to appear vertically. The crack opening widens as the load increases. At 1,99 tonf, three lines previously emphasized become red. This condition shows that the strain is getting larger, so the crack openings are getting larger. When the load was discharged in the unloading step, the opened and localized cracks were gradually closed. At the end of the cycle, Figure 8 shows that residual localized cracks on the beam appeared which is in line with the presence of residual displacement on the sample (see Figure 7). The DIC can capture not only the crack opening but also the crack re-closing along with the residual displacement.

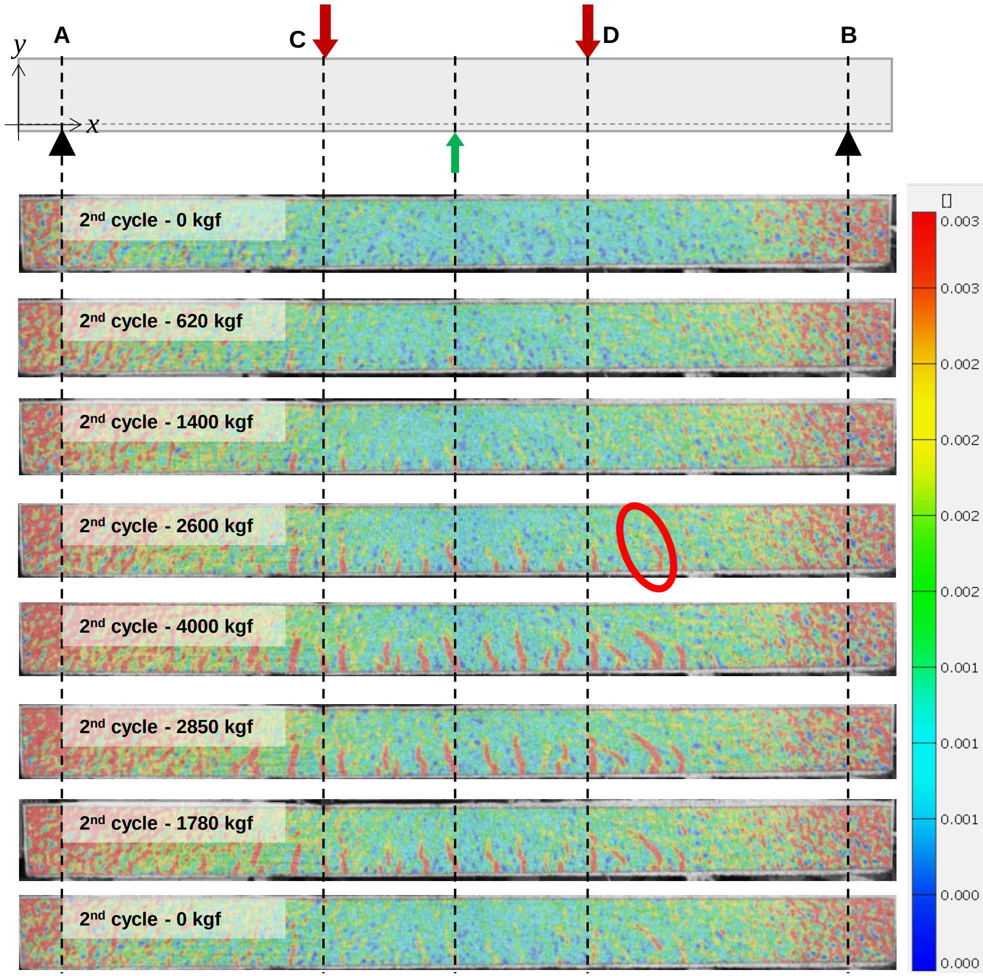


Figure 9. Experimental results using DIC for the 2nd cycle: strain field in major direction (ε_{11})

Further, in the second cycle, residual displacement in the end of the first cycle became the initial displacement, so there are some initial cracks at the beginning of the second cycle. Same as in the first cycle, when the force increases, the crack widens. At 4000 kgf, the peak of the 2nd cycle, the cracks appeared clearly. In the A-C and the B-D area in Figure 9, inclined cracks occurred. It localized at 2620 kgf, forming a flexure-shear crack. Little by little, other inclined cracks were opened in the A-B and C-D zone. At the end of the second cycle, flexure and inclined shear cracks were already opened and the un-re-closed cracks presented.

3.3. Evolution of crack opening

From the strain field in Figures 8 and 9, the location of localized cracks is visible. A further application is the crack measurement on the concrete surface. As we are interested in measuring crack opening in the area of pure flexure (C-D), one crack in the mid-span of the beam is observed and measured as shown in Figure 10 since the first cycle. The curve shows the crack opening evolution in the function of forces subjected to the beam. The complete cycle (loading-unloading) is presented on the left curve, whilst cracks occurred at the increasing force applied is presented on the right curve. The crack opened, re-closed, and re-opened during the test. Evidently, once force was released (unloading), the crack re-closed. As can be seen, at the end of the 5th cycle, as forces were released, the crack was re-closed (see the left curve in Figure 10, the purple one). The residual displacement is 0,44 mm.

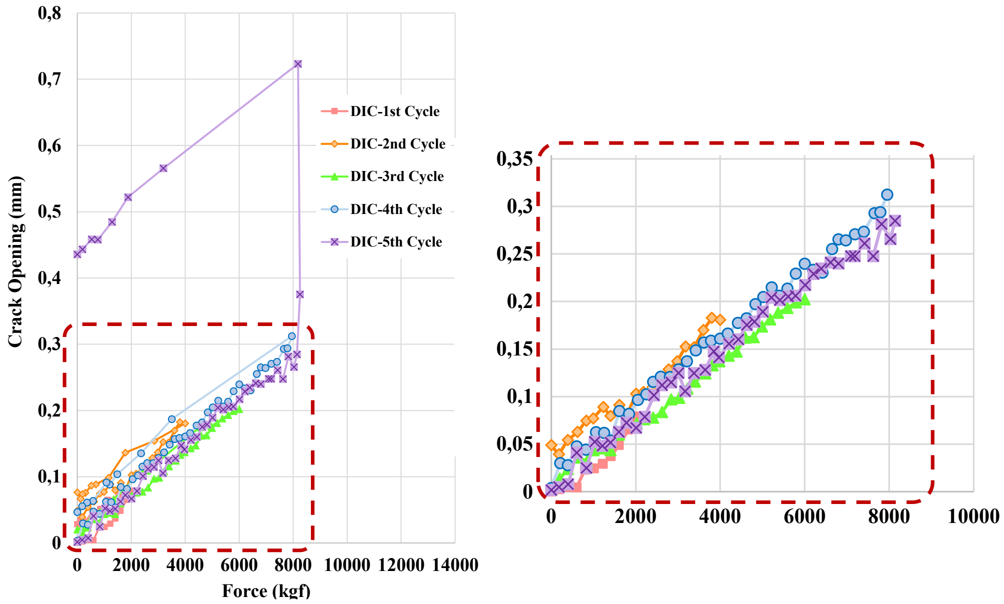


Figure 10. Evolution of crack opening until the maximum load for each cycle

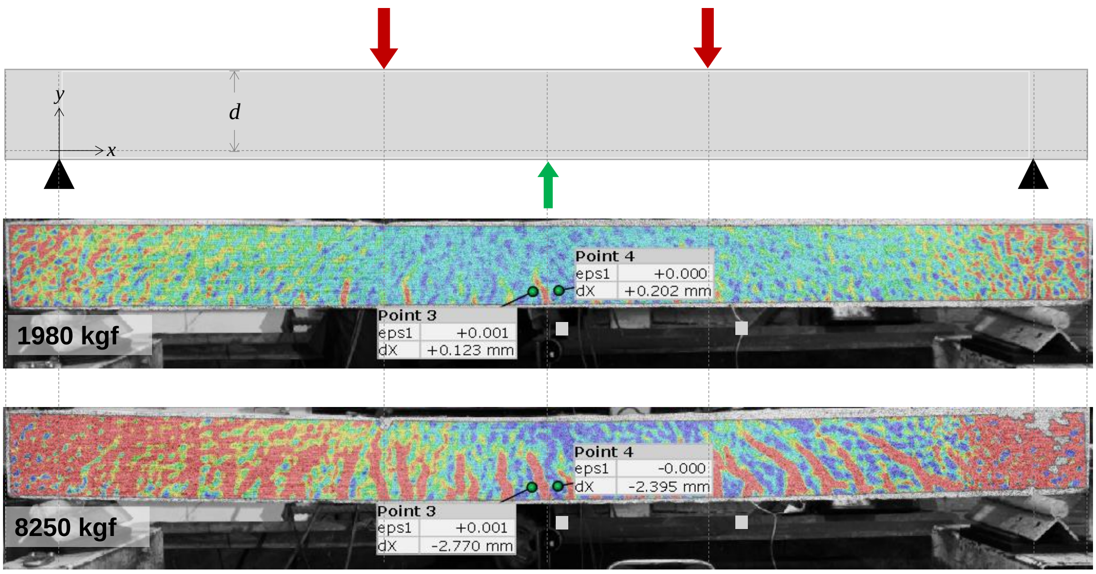


Figure 11. Point of crack measurement on concrete beam surface

4. Conclusion

An observation technique, so-called Digital Image Correlation (DIC) is developed in the Structural and Material Laboratory, Department of Civil Engineering, Universitas Indonesia. Application on the element of structure using alternative material of Oil Palm Shell is presented in this paper. Oil palm shell concrete beam can resist up to 8250 kg of force. The application of DIC as new contactless equipment shows how powerful this technique is. It can capture the displacement as well as the conservative method, in this case, LVDT (dial gauge). Further utilization of the DIC system can capture crack opening, re-closing, and re-opening cracks phenomena following the load application. The fifth cycle of the experiment shows the residual displacement, and it is confirmed from the force-vertical displacement responses and from the un-reclosed crack. Crack measurements can practically be obtained from the movement of the speckles on the surface around the cracks. To sum up, the DIC system is very robust for recording and capturing structural responses. Measuring crack does not need to measure directly on the beam. This contactless system will make it easier for the user to apply in the future long-distance measurement. For future works, the setting of the lighting and the environment of the experiment should be set well to produce better images.

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