Damage Simulation Using Digital Image Correlation Technique Under Review Development for Structural Monitoring

Cintantya Budi Casita[1,2,*][a], Data Iranata[1][b], Budi Suswanto[1][c] and Masahide Matsumura[3][d]
[1]*Department of Civil Engineering, Faculty of Civil Engineering, Planning and Geo Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia*
[2]*Department of Civil Engineering, Faculty of Engineering, Universitas Pembangunan Nasional Veteran Jawa Timur, Surabaya, Indonesia*
[3]*Department of Civil Engineering, Faculty of Engineering, Kumamoto University, Kumamoto, Japan*

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Abstract: For a realistic assessment and forecast of the technical condition of a reinforced concrete, steel, or composite structure during all phases of loading, it is necessary to have precise information regarding the stress–strain state of the structure. Digital image correlation (DIC) is the optimal way for acquiring this information. DIC is a method for identifying contactless structures that involves acquiring an image from an experimental program as a physical object, converting it to digital form, and investigating its behavior in depth. In this paper, a comprehensive examination of theoretical and experimental findings from numerous works is presented. The open-source platform Ncorr built by the MATLAB software, a special capability to recognize this DIC analysis as a support assessment is examined further. To comprehend the parameters, a systematic technique and its correlation were also introduced in terms of image acquisition and post-processing. The findings enable us to use DIC for more accurate stress-strain parameter measurement and structural behavior evaluation.

1 INTRODUCTION

The damage of structural element is now concentrated to be evaluated precisely, since it is related to the performance of the infrastructure. Element structure that interacts with the significant environment or defect by high earthquake need to be repaired before the life span of the structure reached (Alexander et al., 2015; Fu & Larmie, 2005; Halstead, 1986; Interior & Further, 2021; Yang & Li, 2012). Another case, such a long-term operation, moving load, blasting load, or any specific criteria to support the function of structure, necessities specific stress-strain. This particular condition also considered by the material property. Reinforced concrete, steel and composite structure will have a different behaviour in particular to have a response to the effect of the damage (Yang & Li, 2012). Various experimental program and simulation modelling of damaged for any type of structural elements has been studied to accommodate the illustration of reliable assessment. This study is to investigate the actual technical conditions that will give the recommendation as well as to predict the performance with its influence by the variety of external factors (Abhyuday, 2017; Lindvall, 2003a; Maalej et al., 2010).

In order to obtain the fully behaviour for the purposes of the assessment, a high amount of specimens under examination of experimental program need to be conducted, which often impractically difficult (Mccarter, 2010; Taffese et al., 2019). Under numerical modelling, some assumptions need to be included which sometimes not similar to the actual case. Still the further

[a] https://orcid.org/0000-0002-6628-9631
[b] https://orcid.org/0000-0002-2988-3316
[c] https://orcid.org/0000-0003-0274-9800
[d] https://orcid.org/0000-0002-5794-2088

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investigation needs to be verified. Digital Image correlation (DIC) come as the alternative to identify its structure stress-strain state at all stages of loading with high accuracy, which will not be possible conducted by conventional technique. As the information, DIC is a class contactless methods obtaining an image from the actual experimental – physical object then converted into digital form. The result can be plotted then specified the necessary information about stress-strain state (Kumar et al., 2019; Tambusay et al., 2020).

In addition, DIC is also called as an optical metrology technique for measuring surface deformation. It is a full-field image analysis technique used to evaluate the mechanical properties of a specimen by directly measuring displacement. The displacement of the specimen is computed by connecting a collection of images taken before, during, and after loading. The surface geometry is determined by observing a speckled pattern (typically black and white) and monitoring how the pattern deforms when multiple images from the sensor pair are captured in time (Jarrett, 2021; Jones et al., 2018).

This data analysis using a photographic illustration consists of comparison of the surface of the reference image. This reference image compared to the progress loading which in the next condition also compare to the progress loading ahead (Sciuti et al., 2021). DIC technique also correspond to the different of deformation process which is followed by the stress – strain accordingly (Blikharskyy et al., 2022; Chai et al., 2020). Open source Ncorr Program which built on MATLAB is used as the parameter of investigation which provide some promising tool to measure the stress-strain and displacement. It is also a free software that include the postprocessing analysis (Meng et al., 2017; Suryanto et al., 2017; Tambusay et al., 2018a; Z. Zhang et al., 2018).

2 GENERAL REVIEW AND DIC IMPLICATIONS

Since its introduction in the 1980s (Angst et al., 2009; Farshadfar, 2017; Lindvall, 2003b), DIC has functionally considerable used for a broad range of applications across various disciplines, including engineering. It is nowadays popular as a non-contact full-field technique to measure stress – strain, geometry and displacement of materials and structure (Ghorbani et al., 2015; Helfrick et al., 2011). The development of DIC technique to recent development presents in Figure 1. DIC has widely used to section program under laboratory testing where the size and the dimension of the specimen is clearly specified. In some current studies, DIC gain attention in large-scale structural testing due to its benefits for accommodating the testing conditions over point measurement, with a proper distance (Banjare & Rao, 2018; Ghorbani et al., 2015; Hansen et al., 2019b; Helfrick et al., 2011; Bing Pan et al., 2009; Practices

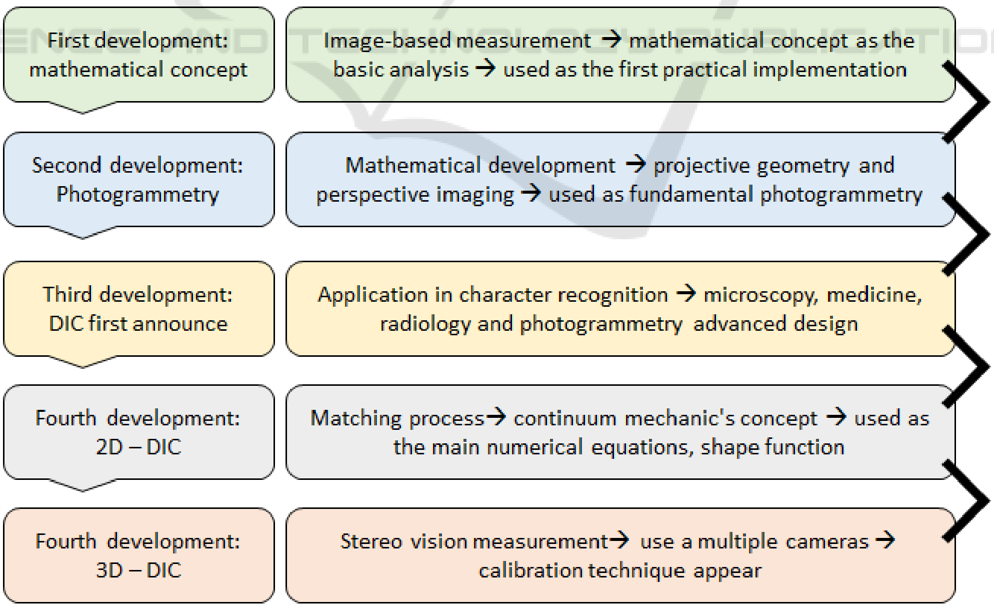

Figure 1: The history review of the development of DIC technique (Sciuti et al., 2021).

& Quanti, 2018; Sciuti et al., 2021). In large amount literatures, DIC also classified as digital speckle correlation method (Blikharskyy et al., 2022; Carolina & Carolina, 2013; Tambusay et al., 2020). Some identified as computer aided speckle interferometry (Alexander et al., 2008), texture correlation (Alexander et al., 2008; Azarsa & Gupta, 2017; Pontevedra et al., 2019), and electronic speckle photography (Helfrick et al., 2011; Bing Pan et al., 2009). Despite of variety of names, DIC in principle based on the digital image processing and numerical computation. In this particular review, 2D DIC method will be more subjected to the measurement since it is easy to be applicated. Somehow, if the test specimen has a curve shape, this technique is no longer applicable (Yin et al., 2019).

It should be concerned that speckle pattern serve as the important rule in DIC method. Burch and Tokarski discovered that a succession of speckles appear when an item is irradiated by a coherent light source, such as a laser. This finding suggests that the speckle pattern is an important rule in DIC method. (Burch & Tokarski, 1968), and These artificial white-light speckle patterns aid in the identification of surface deformation, which is necessary for the research. Later on, Leendertz applied this technique to the measurement of metrological standards. The laser speckle method is typically utilized when tension measurements are being carried out. The laser speckle technique, which is an interference approach, has certain limitations, including the following: It is expensive and requires a testing environment that is extremely steady (free from vibration) (Leendertz, 1970). Other research try to create a new approach that use white light rather than a laser. This method is known as the white light digital speckle technique. In fact, the majority of recent studies on DIC feature white-light speckle patterns, which were created using a white light source or natural light illumination.

After many years of research and investigation, the DIC method has matured into a refined technique (Asundi & North, 1998b; Chiang & Asundi, 1979). DIC has numerous uses, such as measuring displacement (Asundi & North, 1998a), velocity, forecasting failure (Guo et al., 2020), and performing fatigue study. Strain measurement is one of the most useful applications of this technology because of its outstanding accuracy over a wide variety of materials (Ge et al., 2018; Rana et al., 2018; K. Yu et al., 2018; W. Zhang et al., 2018). In this assessment, Pan et al., investigated a various digital image correlation technique (Dong & Pan, 2017; B Pan et al., 2009; Bing Pan, 2009; Bing Pan et al., n.d., 2012, 2016), which have made significant advances in the areas of measurement accuracy, efficiency, and resilience due to their dogged efforts. 2D DIC illustrate to provide some benefits as illustrated in Figure 2.

More significantly, 2D DIC provides some constant images with high resolution that can be used to provide any information related to the specimen identification criteria. This information can include actual cracking and changes in the specimen's geometry, for example. This method also can be applied to many areas. It is possible to state that two-dimensional differential interference contrast (2D DIC) is one of the most well-known and alluring techniques that is widely used for a variety of applications. In spite of this, the 2D DIC methodology has a few drawbacks, which are illustrated in Figure 3.

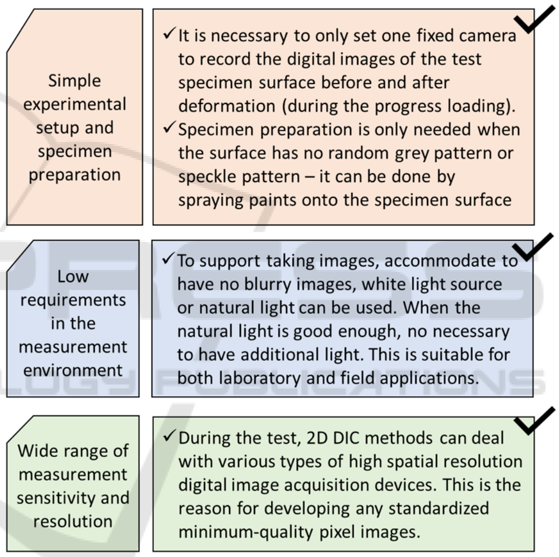

Figure 2: 2D DIC attractive advantages for structural monitoring systems (Bing Pan et al., 2009).

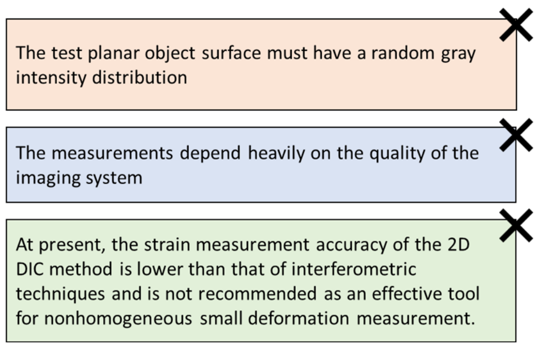

Figure 3: 2D DIC disadvantages for structural monitoring system (Bing Pan et al., 2009).

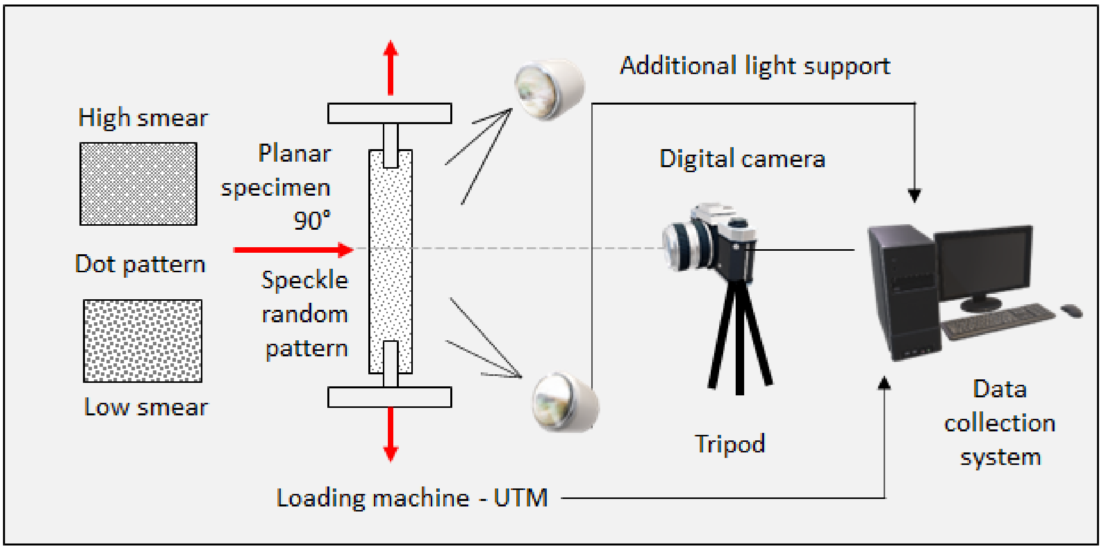

Figure 4: Typical photographic acquisition system for 2D DIC technique (Kumar et al., 2019).

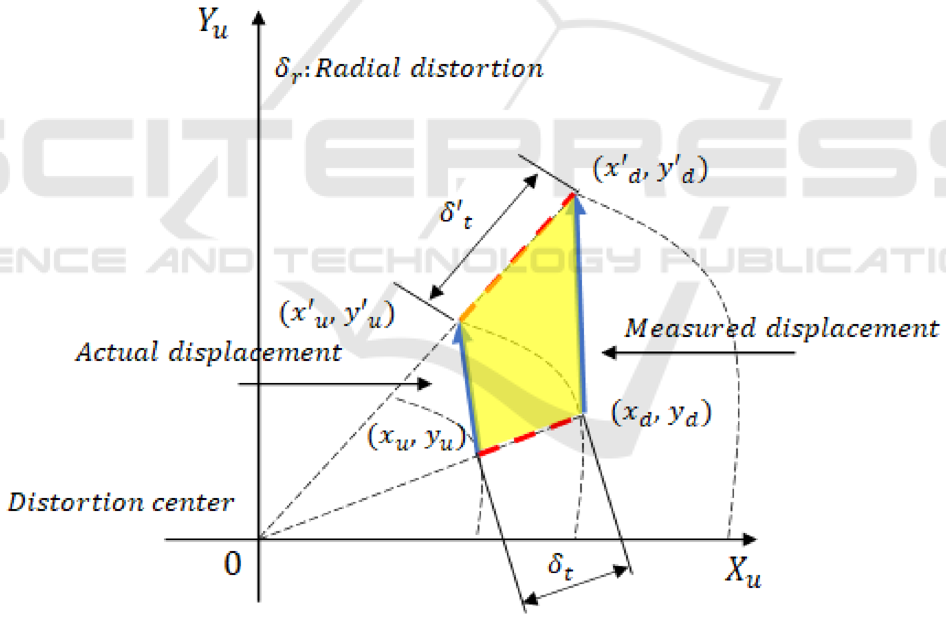

Figure 5: Dot to dot – influence of distortion on the classifying 2D DIC measurement: coordinate before and after loading (Bing Pan et al., 2009).

Despite the fact that there is a great deal of published material available on 2D DIC, there is a shortage of a review study that concentrates on the technical specifics and accuracy analysis of the optical approach that is both straightforward and very popular (Kumar et al., 2019). It would therefore appear to be required to conduct a more in-depth analysis of this strategy. The aim of this review is to systematically give the technical assessment and give the guidance to use advance 2D DIC, especially when it is using opensource software such as Ncorr within a part of MATLAB. The typical condition to take the 2D DIC technique refer to Figure 4 – optical image acquistion (Bing Pan et al., 2009). This DIC also consider as a low cost identification images since any camera can be used for this analysis. For a clear information, influence of distortion of changing speckle pattern is illustrated in Figure 5. This is to measure the displacement based on the progress image (compare first image to the last image after testing).

Implementing the 2D DIC approach typically entails the following three steps, which must be completed in that order: (1) setting up the specimen and experiment; (2) taking pictures of the planar specimen surface both before and after loading; and (3) utilizing a computer software to process the pictures in order to extract the needed displacement and strain data. The topics of specimen preparation and picture capturing are introduced initially in this section (B Pan et al., 2009; Taylor et al., 2010). The fundamental ideas and concepts of 2D DIC are then explained. For support characteristics, some studies also included, to have a proper understanding of the the materials properties i.e., steel (Casita et al., 2022; Casita, Sarassantika, et al., 2020; Casita, Wibisana, et al., 2020), concrete (Komara, Wahyuni, et al., 2019; Pertiwi et al., 2021; Susanti et al., 2021) and composite materials (Komara, Tambusay, et al., 2019)

2.1 Specimen Preparation

The schematic illustration of DIC system presented in Figure 4. This kind of set up generally implies for 2D DIC method (Kumar et al., 2019). The test specimen requires to have random speckle pattern. To provide the pattern artifical technique normally be made by spraying black paints with the initial white painting as the based of the surface. This based painting is necessary when the surface colour representing a not clear area.

To accommodate the better visualitation, a flat contour normally be provided for each specimen. Patterning also one important parameter, the most frequent way of patterning in DIC is to apply a solid white background followed by a random black speckle pattern (Alaswad et al., 2018; Kim et al., 2018). Even when alternative patterns are utilized, the pattern applied to the surface of a specimen is typically known as a speckle pattern. To ensure that each subset is distinct, it is necessary to apply a speckle pattern with recognizable, distinct, random features throughout its region (Dong & Pan, 2017; Xu et al., 2017). Thus, parameters like speckle size (Reu, 2015), pattern contrast (Sciuti et al., 2021), edge sharpness of the speckle (Thai, 2020), and speckle density (Jarrett, 2021) must also be considered.

For the DIC algorithm to recognize a pattern as non-repeating and isometric, there must be enough contrast between the pattern's light and dark portions for each unique feature to be recognized (Reu, 2015). The contrast of the pattern is affected by elements like as the strength of the light source, the aperture of the lens, the exposure duration of the camera, and the type of paint used for the speckle (Jones et al., 2018). If an image region is oversaturated or underexposed, the DIC algorithm may wrongly correlate or drop portions. Therefore, portions of a speckle pattern with low contrast will enhance the noise of a DIC measurement (Sciuti et al., 2021).

The speckle density relates to the quantity, size, and distance between individual features in a speckled pattern. The speckle density effects the size of a subset and, consequently, the spatial smoothing and noise of DIC displacement data. Effectively, the smaller the speckle size that can be identified by the algorithm, the smaller the subset size that may be applied. The good practices guide produced by the International DIC Society (iDICs) specifies the best feature density as 50% dark to light features, with 3-5 pixels as the recommended size for one feature (Jones et al., 2018), where a feature is defined as a distinct speckle dot or form within the speckle pattern.

There are various ways to create a successful speckle pattern. Commonly, the surface of the specimen is sprayed with a solid backdrop of white spray paint, followed by misting the surface by spraying black paint into the air and allowing the droplets to land on the surface (R B Berke et al., 2016; Ryan B. Berke & Lambros, 2014; Ryan B Berke & Lambros, 2014). A similar method includes airbrushing black paint over the surface to produce a black-and-white pattern (Hansen et al., 2019a). Another method employs toothbrush bristles to flick black paint across the specimen's surface (B. Yu et al., 2017).

The challenge to prepare the images in this measurement relate to the camera and lens requirement and also the effective distance to position the camera. This parameter relates to the spatial resolution of each images (Practices & Quanti, 2018; Thai, 2020), which considers to visualize the stress – strain characteristics. To prevent having distortion and blurry images. some recommendation to aquire 2D DIC method ilusrated in Table 1.

Table 1: Recommendation of DIC techinque (Blikharskyy et al., 2022).

DIC pattern	Concept
High contrast	Dark black dots on a bright white background on bright white dots on a dark black background
50% coverage	Equal amounts of white and black on the surface

DIC pattern	Concept
Consistent speckle sizes	At least five pixels in size
Isotropic	No bias in any particular orientation
Random	Nor repetitive

2.2 Data Acquisition

From the process of experimental program, digital images is recorded during the phase of loading. During the process, stress – strain will be developed in the region of interest. The accuracy of the result may be obtained by the resolution of the images which is considered to have a proper zoom in analysed area (Blikharskyy et al., 2022). A previous research recommend to have subset size in pixels 64×64 under resolution of image 250 pixels/mm. Additional light may be added according to the actual conditions. Ghani et. Al., implied the research using 4.288×2.848 pixels with a setup of Nikon D90 (Ghani et al., 2016). Another characterized as a low budget DIC camera, using low to medium acquisition speed with 5 M pixels at the sampling speed at 0.2 Hz , or the research with 3.2 M pixels with the speed up to 121 fps (Blikharskyy et al., 2022).

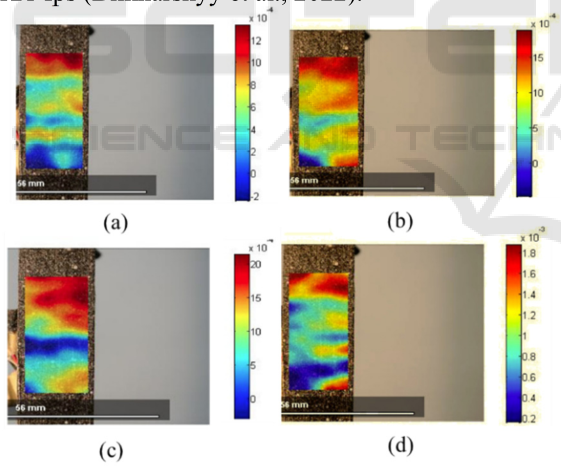

Figure 6: Data acquisition 2D DIC – matching to uniaxial test method (Ghani et al., 2016).

As the setup of DIC completed, the integrated test also prepared in parallel, to plot stress – strain curve using uniaxial testing machine matching with the load cell and LVDT. Some illustrations given as follow to record the acquisition of images in accordance to Gani, et. al. (Ghani et al., 2016). This study illustrating the process of 2D DIC using Ncorr opensource program based on MATLAB. The data acquisition taken from tensile testing of coupon steel specimen, where the speckle pattern provided by black paint as the based and sprayed by white paint using air spray. The loading cited to take the illustrated images for each step respectively, 0.5 kN, 1, kN, 1.5 kN and 2.0 kN.

2.3 Ncorr Program

Ncorr is an open source 2D digital image correlation MATLAB software. It employs numerous unique 2D DIC methods, is entirely contained within the MATLAB environment, and includes plotting tools for the generation of figures.

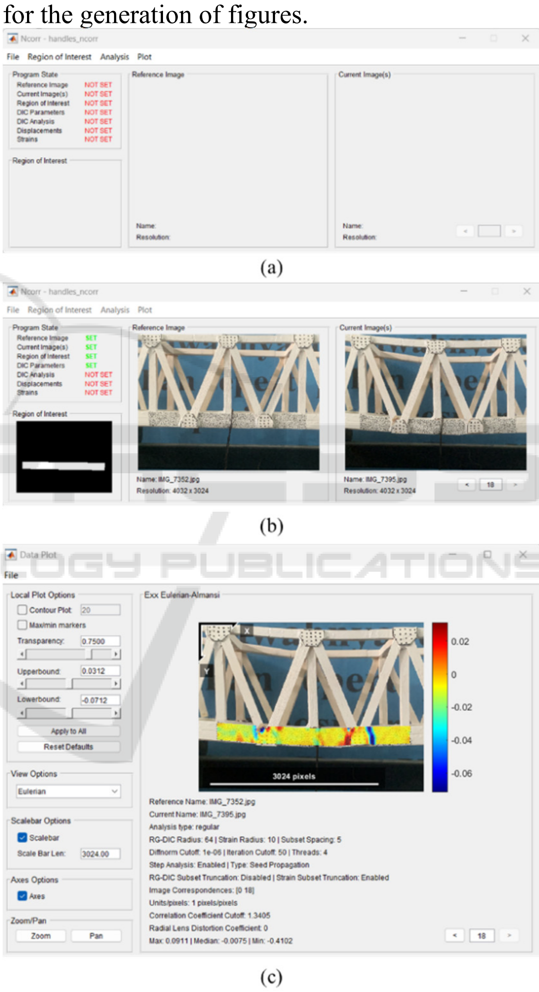

Figure 7: (a) Ncorr main interface, (b) Second interface after loading reference image, (c) Strain profile.

The computationally expensive algorithms are optimized with C++/MEX, while the GUI is primarily written in m-code. The objective is to give the users an easy to use, efficient, and versatile DIC application. In detail the use of Ncorr is to aims several objectives; (1) develop a strong, open-source code for 2D digital picture correlation, (2) provide resources for the use/understanding of the software and the underlying DIC algorithms, and (3) display applications and examples of the program, (4) receive constructive input from users to help improve the application and resources on this website (Suryanto et al., 2017; Tambusay et al., 2018b).

The main menu of Ncorr program is illustrated in Figure 7(a), which included to identify the reference image - the image before loading. To obtain the specify section area to undertake stress – strain, the object needs to be classified to small subset. Each subset need to be have a special pattern, so the program can distinguish the similarity. This small subset evaluated by subset radius parameter, *r,* and subset spacing parameter, *s*. In this program, the deformation is assumed to imply homogeneously (Francesca et al., 2018; Ghani et al., 2016; Meng et al., 2017). Apart from the feature provided by Ncorr, the program also supports to handle multi-thread computation. For more information on the development of the program, can be found http://www.ncorr.com/.

The local displacement vector is formed, and the deformation inside each subset is computed, based on the location of the center-point of the subset, which is present in both the reference picture and the target image. In order to acquire the whole displacement map, which is necessary for deriving strains, this method must be performed for each and every subset block that covers the entire surface of the object (Dong & Pan, 2017).

Figure 7(b) displays the main interface of Ncorr program after input reference image. One things after open the program on MATLAB, the images with the same file name need to be uploaded and this will then displayed on the main screen. Then, those images that is taken during the loading process uploaded after. In the next step, the region of interset needs to be clarified as inform on the Figure 7(c). Figure 7 presents the an example illustration of the strain maps after processing the 2D DIC analysis.

3 CASE STUDY – STEEL STRUCTURE

The research focused by Yoneyama, et al., on the 2D DIC under experimental program of a simple beam structure. The test set up is for flexural beam within the concept of three points bending. The deflection is the objective of this study in terms of classifying DIC method under structural element with variety of speckle pattern. A wide flange beam element 500cm×20cm×0.8cm is used with the steel grade of SS400. The modulus elasticity is 210 GPa with the moment inertia 16×10^6 mm^2. The quality of the images set up to 3504×2336 pixels using a normal lens and a shift lens. The speckle random pattern placed using spraying gun with a white color (Yoneyama et al., 2005).

From those images in Figure 8, it is obvious that high accuracy measurement provided with the specimen with random pattern. The deflection of the specimen without pattern represent no accurate deformed shape on the digital illustration (Yoneyama et al., 2005).

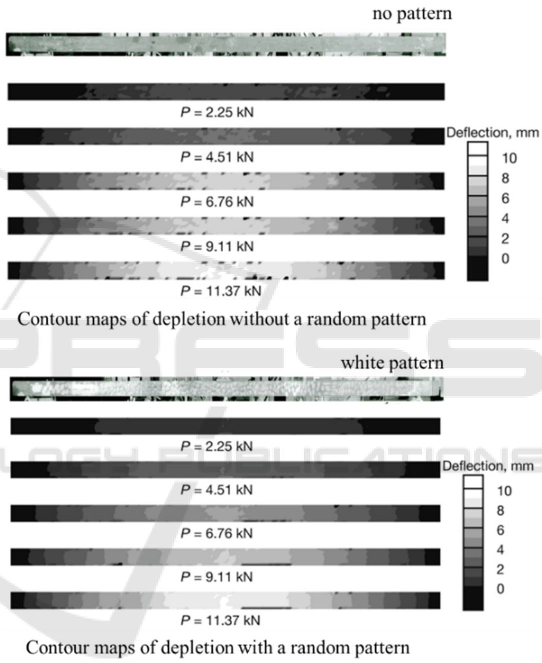

Figure 8: Illustrated 2D DIC obtained by two different condition – with and without random speckle pattern vs. normal lens and shift lens (Yoneyama et al., 2005).

Further investigation conducted by Arola, et. al., under ultra-high strength structural steels (Pontevedra et al., 2019). The test conducted on UTM machine. The objective of the research is to measure the bending force which relate to the punch stroke corresponding to bending angle. Then 100mm×150mm×6mm rectangular are investigated. The speed rate for the experimental program used as 0.7 mm/s. The illustrated set up and specimen are presented in Figure 9, where the digital camera positioned under the specimen. With this study, a better understanding of the behaviour of ultra-high strength steel under bending conditions can be evaluated. More detailed information can be found and assessted as parameter analysis on the optimal strain calculation.

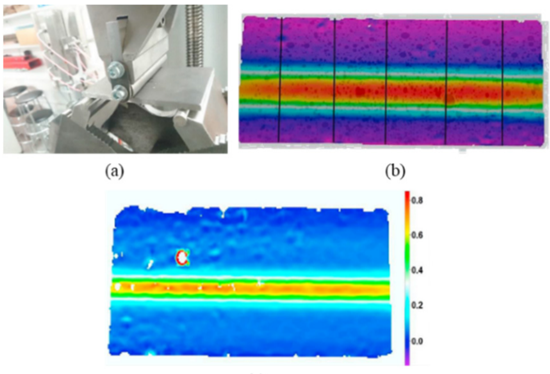

Figure 9: (a) Uniaxial bending test of steel plate specimen; the position of the camera to take the images is below the specimen, (b) 2D DIC taken from the bottom of the plate – seen from the deform axis, (c) homogenous strain surface (Pontevedra et al., 2019).

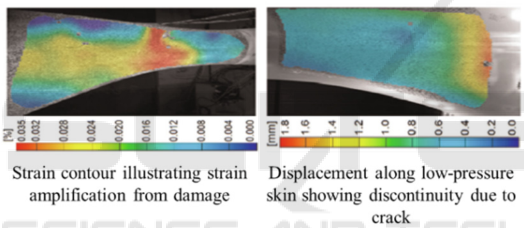

Figure 10: Damage detection results using DIC technique (Janeliukstis & Chen, 2021).

Another implementated large scale structural testing application introduced by another researchers, Leblanc et. al., identified the damage of water turbine blade using full-field DIC measurements (see the Figure 10). This analysis detecs the damage location coming from the stress concentration arising from the load. Sufficient illustrations found in good agreement with finite element simulation results (Janeliukstis & Chen, 2021). Interesting structural system also represent in 8-feet diameter cylinder shell which investigated the effects of buckling parameter (Janeliukstis & Chen, 2021) as illustrated in Figure 11.

It is confirmed that the change phase of each step of loading can be provided by DIC measurements. This valuable illustration can assess high accuracy to determine recommendation and selection criteria considering the size, position and dimensions. The data capture from DIC also allowed for the determination of crack length measurements during

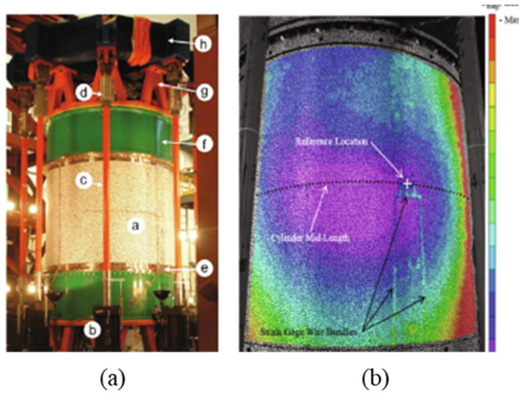

Figure 11: (a) Specimen configuration – a shell cylinder use for drainage hollow, (b) measured of stress-strain plane (B Pan et al., 2009).

the experiment. This crucial performance and material characterisation can aid in the creation of finite element analysis models for the prediction of composite failure and lead to design enhancements (Dong & Pan, 2017; Janeliukstis & Chen, 2021).

4 CONCLUSIONS

Reclusively, the DIC technique has been widely used for variety of specimen; start from small specimens to large full-scale structures, but less so for testing steel structure especially in the connection. This review focuses on the basic parameter and example of recent study of the DIC measurements. Ncorr program represent one of the alternatives which is applied globally. Some findings are taken as the consideration as follows: (1) preparation phase consider as the important part to identify the results of observation i.e., images quality, pattern condition, effective distance and surface of the specimen followed by the lightning conditions, (2) to accommodate the accuracy, controlled evaluation of the experimental program also needed. Emphasises are specially placed on the displacement. (3) concern as the easy application of analysis, 2D DIC come as a great alternative but limited for in-plane deformation. For the complex component such as multi-shaped product, curved shaped surface and etc, the advanced evaluation needs to use 3D DIC. It is more practical and effective, but high use of technology needed. It is believed that 3D DIC will more gain applications in the near future.

Further work will focus on a number of prospective avenues for extending the existing research, Future research will focus on a number of prospective avenues for extending our existing research, such as high-performance hybrid CPU and GPU parallel computation to further improve the computation efficiency in order to accomplish real-time measurement by balancing the computation jobs within them. In addition, the measurement accuracy near the crack is frequently low, so it is still necessary to develop high-accuracy DIC measurement in the case of a fracture by detecting the crack based on the significant changes in displacements and assigning different weightages to the pixels in the deformed subsets based on the position of the crack.

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