International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:7, 2015

Developing Three-Dimensional Digital Image Correlation Method to Detect the Crack Variation at the Joint of Weld Steel Plate

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***Abstract*—**The purposes of hydraulic gate are to maintain the functions of storing and draining water. It bears long-term hydraulic pressure and earthquake force and is very important for reservoir and waterpower plant. The high tensile strength of steel plate is used as constructional material of hydraulic gate. The cracks and rusts, induced by the defects of material, bad construction and seismic excitation and under water respectively, thus, the mechanics phenomena of gate with crack are probing into the cause of stress concentration, induced high crack increase rate, affect the safety and usage of hydroelectric power plant. Stress distribution analysis is a very important and essential surveying technique to analyze bi-material and singular point problems. The finite difference infinitely small element method has been demonstrated, suitable for analyzing the buckling phenomena of welding seam and steel plate with crack. Especially, this method can easily analyze the singularity of kink crack. Nevertheless, the construction form and deformation shape of some gates are three-dimensional system. Therefore, the three-dimensional Digital Image Correlation (DIC) has been developed and applied to analyze the strain variation of steel plate with crack at weld joint. The proposed Digital image correlation (DIC) technique is an only non-contact method for measuring the variation of test object. According to rapid development of digital camera, the cost of this digital image correlation technique has been reduced. Otherwise, this DIC method provides with the advantages of widely practical application of indoor test and field test without the restriction on the size of test object. Thus, the research purpose of this research is to develop and apply this technique to monitor mechanics crack variations of weld steel hydraulic gate and its conformation under action of loading. The imagines can be picked from real time monitoring process to analyze the strain change of each loading stage. The proposed 3-Dimensional digital image correlation method, developed in the study, is applied to analyze the post-buckling phenomenon and buckling tendency of welded steel plate with crack. Then, the stress intensity of 3-dimensional analysis of different materials and enhanced materials in steel plate has been analyzed in this paper. The test results show that this proposed three-dimensional DIC method can precisely detect the crack variation of welded steel plate under different loading stages. Especially, this proposed DIC method can detect and identify the crack position and the other flaws of the welded steel plate that the traditional test methods hardly detect these kind phenomena. Therefore, this proposed three-dimensional DIC method can apply to observe the mechanics phenomena of composite materials subjected to loading and operating.

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***Keywords*—**Welded steel plate, crack variation, three-dimensional Digital Image Correlation (DIC).

I. Introduction

SPEICAL geographical environment and poor geological conditions coupled with the steep and short river are hard to accumulate and drainage rainfall effectively in Taiwan. Especially, Taiwan is located in the Pacific seismic belt and storm-prone regions. It also does not attach importance to environmental conservation in the past, mountainside cultivation, resulting in land cannot be protected effectively. Otherwise, Taiwan will be affected by typhoons, heavy rain, earthquakes and drought and other natural disasters hit. In recent years, Taiwan Chi-Chi earthquake caused loosening of soil and stone of mountains or even collapse. In addition, effects of global warming are going to ferment gradually to induce El Nino and anti-El Niño continue to recur, causing heavy rainfall frequency and intensity will vary with the Earth's temperature rises gradually; such as torrential rains of typhoon Morakot caused landslides in mountainous areas, hit southern Taiwan, causing heavy losses of lives and property of the people, it also leads to water storage capacity of Tseng-Wen reservoir etc. drastically reduce and even threaten the safety of reservoir. Landslide of National Road 3 at Taipei-Keelung section happened without any sign to cause losses of human life. Otherwise, 311 strong earthquake causes tsunami in Japan on 2011. Pakistan earthquake of July 2013, with the exception of houses toppled and loss of human life, and even reached a small island off the coast. These exceptionally natural disasters caused by climate disaster and aftermath yet very serious, these are the effects and consequences of global warming. Hydraulic gate is applied in water dam to store and drain water. High tensile strength of steel plate is used as constructional material of hydraulic gate. But, there are maybe some cracks and rusts, induced by the defects of material, bad construction and seismic excitation and under water respectively, thus, the mechanics phenomena of gate with crack are probing into the cause of stress concentration, induced high crack increase rate, affect the safety and usage of hydroelectric power plant. In fact, most of the damage is progressive, meaning that there are usually signs of long-term, such as unusual changes in the development of cracks, seepage. The test and maintenance of hydraulic machinery can reflect these kind problems. Hydraulic gate includes rail, chair, water seal, and guide such groups stand gate slot and buried in concrete. Gate rubber seal around the door, align it with the door frame seal tight, door and gate installation guide shoe on both sides to cooperate with frame guide bracket [1]-[8].

Due to the fixed hydraulic gate is a steel structure in water. It is inevitable because the hydraulic gate will be rust with its high water pressure. The bearing capability of fatigue limits of this kind gate can be reduced because of a small corrosion to cause risk of hydraulic gate. There are two kinds of connection of steel fixed hydraulic gate such as: riveted and welded. The design, manufacture and installation of fixed hydraulic gate is not only the need to comply with the design requirements of the code, but also more consistent with the principles of economic development and environmental conservation. Especially hydroelectric power plant's service life is quite long, so construction and material quality is more important. Some of research cases are found that the reasons of shorter of life span of hydraulic gate or security incidents are defects of material and construction method. Thus, this research focuses on the cracks in steel plate to develop the digital image correlation method to investigate the cracks variation of steel plate with cracks for fixed steel hydraulic gate. Analysis on strain distribution of civil and mechanical engineering and other related fields, especially with heterogeneous materials as well as the stress concentration problems, is extremely important and indispensable measurement techniques. Conventional strain measurement techniques can be divided into two main fields [9]. One for aiming at a specific location within a two-point position, strain measurements for strain distribution of deformation of material surface could not be obtained. The second is before deformation in manufacturing grid on the specimen surface, directly after the deformation calculation of displacement of the grid, and to estimate the strain fields of the grid, but the analysis process will take a long time. Precision strain measuring instruments such as Raman Spectroscopy and Electrical Speckle Pattern Interferometer, although can be carried out in a non-contact manner surface strain measurements, but because of expensive equipment and stability and other factors, could not be widely used in science or engineering. Digital image correlation method [10]-[12] is the latest optical measurement technology can provide full strain distribution of low price and high precision, the strain analysis tool is suitable for promotion. Therefore, the digital mage correlation method is applied to detect and analyze the strain variation of steel plate with crack under loading.

II. Methodology

The DIC method can be divided into two categories – two-dimensional DIC and three-dimensional DIC. The main hypothesis of two-dimensional DIC method is that the distance between the image acquisition instrument and the specimen keeps constant during the test. Therefore, it is suitable for the plane strain test or the test without obvious out of plane deformation. If there exists a large out of plane displacement or the specimen surface is not a plane, then the three-dimensional DIC method is necessary for the measurement. The three-dimensional DIC method utilizes the same image identification principle as the two-dimensional DIC method. The principle of the two-dimensional DIC method and the method to determine the three-dimensional method of the specimen surface will be introduced as below.

A. Two-Dimensional DIC Method

The principle of two-dimensional DIC method is to determine the local correlation of two images. The local correlation is used to identify the mapping relationship between the images before and after deformation. The structural speckle will be manufactured on the specimen surface. This makes a different grayscale distribution in the image. This grayscale distribution characteristic is utilized to identify the corresponding position of images before and after deformation.

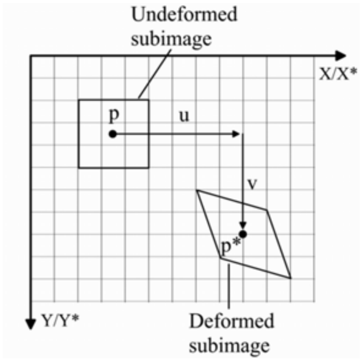

Fig. 1 Schematic drawing of relative location of sub-images of deformed and un-deformed images on surface

As shown in Fig. 1, central point prior to deformation is point P, and then changed to point P* after deformation, the correlation between P and P* can be determined by using the correlation coefficient [6], [7]:

$$COF = \frac{\Sigma g_{ij}\tilde{g}_{\bar{i}\bar{j}}}{\sqrt{\Sigma g_{ij}^2 \cdot \Sigma \tilde{g}_{\bar{i}\bar{j}}^2}} \tag{1}$$

where, g_{ij} and $\tilde{g}_{\bar{i}\bar{j}}$ is grayscale of sub-image *A* on coordinate (i, j) and sub-image *B* on coordinate $(\bar{i}, \bar{j})$ respectively. And, coordinate $(\bar{i}, \bar{j})$ of sub-image *B* corresponds to coordinate (i, j) of sub-image *A*. The maximum correlation coefficient is equal to 1. It means that the sub-image *B* is exactly the image of sub-image *A* after deformation. Therefore, we are looking for the position which yields the maximum value of the correlation coefficient during the analysis.

B. Three-Dimensional DIC Method

If the horizontal distance for the camera to move to the right (or the object to move to the left) is "*e*", the horizontal displacements on the photosenstive element is "$\overline{AA'}$" for a relatively closer point "*a*", and "$\overline{BB'}$" for a relatively farther point "*b*" as shown in Fig. 2.

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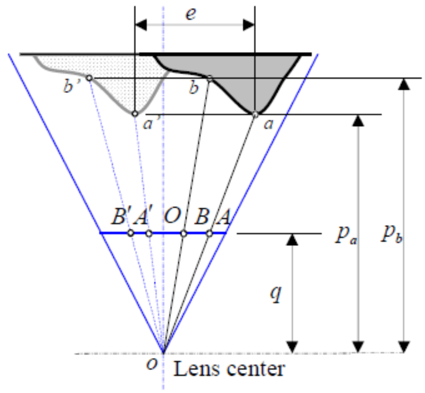


Fig. 2 The parallax phenomenon caused by the difference object distance

The geometric relationship is:

$$\overline{AA'} = \left(\frac{q}{p_a}\right)e \tag{2}$$

$$\overline{BB'} = \left(\frac{q}{p_b}\right)e \tag{3}$$

where: q, p_a and p_b are the distance between center of lens and photosensitive element, point a and point b respectively. The horizontal movement on the sensing element is expressed in pixels, thus:

$$N_{AA'} = \gamma\left(\frac{q}{p_a}\right)e \tag{4}$$

where: γ is the number of pixels of a unit sensing element in $pixels/mm$; $N_{AA'}$ is the horizontal displacement of "a" in pixels. Because the correct values of γ and q are unknown, these two parameters can be combined into a single parameter "Λ". Hence:

$$\Lambda = \gamma q \tag{5}$$

Equation (5) can be re-written as:

$$\Lambda = \frac{N_{AA'}p_a}{e} \tag{6}$$

Once the calibrated value of Λ can be found using regression analyses; the distance between two points can be calculated:

$$p_b = \frac{\Lambda}{N_{BB'}}e \tag{7}$$

Knowing the distance between two points, the horizontal and vertical distances of the object to the lens center (x,y) can be found. Equation (7) can be used to calculate the distance of any object "b", and the theoretical error can be estimated by differentiating the equation:

$$dp_b = \frac{-\Lambda e}{N_{BB'}^2}dN_{BB'} \tag{8}$$

Equation (8) indicates that the error is inversed proportionally to the distance between the object and the camera distance. Hence, a greater camera distance will lead to results that are more precise. Therefore, when the camera is horizontally moved "e" distance, the horizontal displacement in pixels of "a' on the sensing element is $N_{AA'}$ based on the relationship to approximate triangular form. If the horizontal coordinate of a with respect to the lens center is x_a , its relationship to the photo horizontal coordinate X_A fits the following relationship:

$$\frac{x_a}{X_A} = \frac{e}{N_{AA'}} \tag{9}$$

Moving the terms, one obtains:

$$x_a = \frac{X_A e}{N_{AA'}} \tag{10}$$

Similarly:

$$y_a = \frac{Y_A e}{N_{AA'}} \tag{11}$$

III. Plan of Pilot Study

Due to stress concentration will affect the strength and safety of material, also they are hard to measure the stress concentrations for these kinds of experiments because the effect of micro-cracks or material heterogeneity. Otherwise, cracks or heterogeneous positions are belonging to mechanics of singularity. Singular stress (Strain Concentration) occurs in extremely small range. Stress Intensity Factor is often used to evaluate the material in specific stress rupture strength of pointers for the failure. Infinite small element analysis method and finite difference method are applied to analyze the mechanics variation of plate with crack under loading. In order to investigate the actual mechanics variation for this kind of plate, the digital image correlation method (DIC) is developed by our research team, and used to measure the stress concentration phenomenon of cracked plate under tensile test. In a process of macro photography, made the crack tip micro-imaging (FOV is 8.46mmx5.49mm) and then to analyze the displacement and strain field of this kind plate. Main focus of this study are described as follows: (1) Fabrication of welded specimens: Welded steel parts are belonging to the heterogeneous material, so this study investigated the influence of heterogeneity on stress concentration of crack tip, or crack of steel plate and solder two materials is at the junction of the cut-off point. In order to be as close as possible to the interface material heterogeneity, the test specimens should be well controlled. Therefore, this welding specimen is taken one-side fillet welding. That is two butt plate-docking, cutting in a 45 degree incline. (2) Surface processing for specimens for image analysis: using DIC method to measure the surface of specimens, measuring surface should have a smooth surface, or strain due to dented error, may be greater than the experimental strain, thus losing test. Welding surfaces are actually extremely rugged. For this reason, steel welding of specimen will be milled about 3 mm by milling machine on both sides of this test material. In order to obtain a smooth surface and eliminates surface discontinuities caused by material in the welding process. This will enable the production of artificial crack tip and crack to meet the objective of this experimental study on behavior of heterogeneous materials. Line cutting without sheet steel on one side of the cutting slope produces an artificial fracture with 10 mm long and 0.38 mm wide. (3) Keep the spacing of the camera and test specimen: take macro photography, camera distance from the specimen is extremely small. According to the process of loading in the tensile test, it causes the change in distance between camera and specimens to induce big measuring error of strain. In order to maintain the distance between camera and specimens, a camera clamp is designed to hold the camera fixed on the specimens. Movement of camera follows the test specimen, then the distance between camera and specimens can be easily maintained.

Fig. 3 Shimadzu 1000kN

Fig. 4 Canon EOS-50D

In this study, a universal testing machine-Shimadzu 1000 kN, Fig. 3 is used to test these test specimens. In addition, Canon EOS-50D ocellus camera, shown in Fig. 4, collocated with Canon Macro Lens 60mm USM is applied to detect the high quality digital images. This Len can reach the effect of 1:1 short range film. Otherwise, the 72 mm of Kenko Extension Tube is adapted to 1:3 magnifying power. That is the image range of practical usage of FOV is 8.46 mm x 5.49 mm.

IV. Test Results and Discussions

This test is used the microcosmic photography, therefore, a tiny crevice about 0.34~0.41 mm is made by line saw, shown in Fig. 5. After image analysis, there are 190~230 pixel width for the width of crack. The average one pixel is about 1.78 micron after calibration. Then, magnifying power for test sample is about 2.64, for the sensitization component 22.3x14.5 mm, the FOV is about 8.45 x 5.49 mm. according to fix the camera at the bottom of crack, this camera is relative to the horizontal displacement of this specimen along the increase of crack development. This displacement does not affect the precision degree of strain measurement; however, it affects the range of measurement. The loading test procedure is shown in Fig. 6.

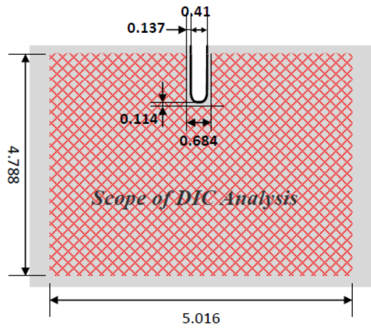


Fig. 5 Sketch of DIC measuring range

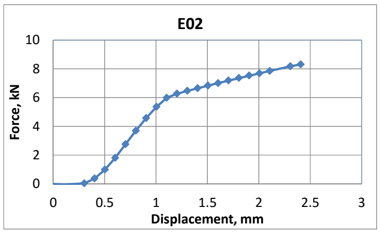


Fig. 6 The loading test procedure

Welding is applied to weld the steel plate to fabricate the hydraulic gate. There are many factors to cause the cracks at the joints of steel plate. Steel plate with crack will be increased by the process of loading. Therefore, in order to investigate the crack variation, parallel with welding bead at the interface of bi-material, the test specimen is fabricated to show in Fig. 7. The materials properties of welding and steel plate are close to each other. Especially the shear modulus and poison ratio are almost the same. Test results for this specimen under the loading of 14.43 kN, 18.27 kN , 20.10 kN and 26.00 kN are shown in Figs. 8 (a)~(d).

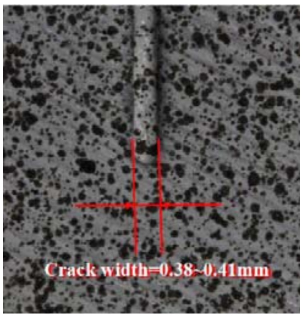
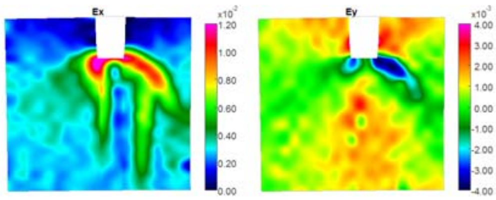
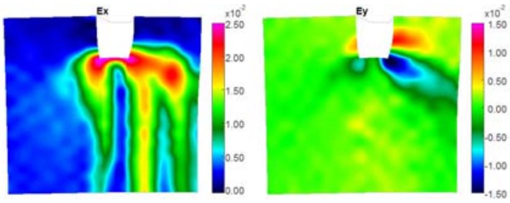


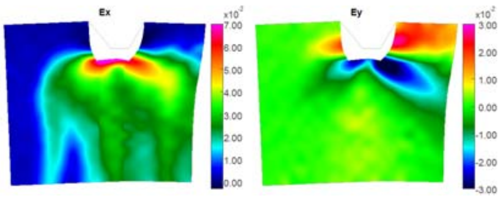
Fig. 7 The man-made crack



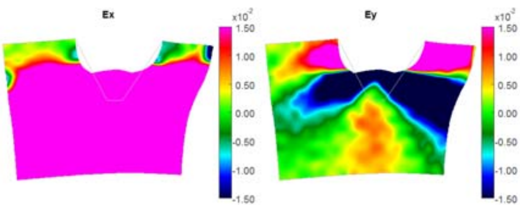
(a) Loading = 14.43 kN



(b) Loading = 18.27 kN



(c) Loading = 22.10kN



(d) Loading = 26.00kN

Fig. 8 Test and analysis results of crack parallel with welding bead at the interface of bi-material

Test results of Figs. 8 (a)~(d) display that the strain variation at the crack tip of welding parallel with the interface of bi-material vary tremendously. The strain will be increased follows the increase of loading, shown in Figs. 8 (a)~(c). Especially, the minus strain is happened at the steel plate; otherwise, the pressured area is happened at the welding area, but it is restrict. Although the shear modulus and poison ratio of welding area are almost the same as those of the steel plate, but the strength of welding area is higher than it of steel plate. When the loading is higher than 22.10 kN, the large deformation is happened on both side of welding and steel plate. This phenomenon shows that this loading exceeds the yielding strength of welding and steel plate to cause this large deformation. Otherwise, the deformation tendency is in favor of the side of steel plate.

V. Conclusions

In this study, the test results of this DIC method found that when the steel plate with crack started to under loading, the vicinity of crack tip produced the pressure area. This phenomenon of pressured area around the vicinity of crack tip cannot be detected by the traditional experimental method. Artificial crack of steel plate is cut by the milling machine for fabricating test specimen. Therefore, these digital image data from test results reveal that artificial fracture at the tip of steel plate with crack under loading display pressured area. This crack area leads the direction of crack development. According to the pressure area produce at the tip of steel plate with crack, the pressure area will be expanded to induce buckling phenomenon, it also leads to rapid deterioration of steel plate. The material property of this test steel plate is non-homogeneous, strain variation of single steel plate under the loading display this phenomenon. Actually, strain variation is affected by the poison's ratio. Otherwise, this DIC method can identify the local buckling area around the tip crack of this steel plate accurately and exquisitely. From test and analysis results of Fig. 8, these results show that the strain variation affected by the weld path tremendously between the interface of the steel plate and weld path. Negative strain area happens around steel plate area, pressure area of weld path increases restrictedly along the increase of loading. This phenomenon becomes obvious when the increase of loading because that the yield strength of steel plate is lower than that of weld path. According to the test results of this research, this DIC technique is useful for analyzing the mechanics behavior of materials.

Acknowledgment

The authors would like to acknowledge the support of Ministry of Science and Technology, Taiwan through grant No. MOST-103-2625-M-260-001 and MOST-103-2625-M-167-001.

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