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Visualization of Buckling on Thin-walled Cylindrical Shell by Digital Image Correlation Method

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Abstract: The problem of buckling stability is very important in thin-walled cylindrical shell structure. In order to investigate the buckling phenomena, digital image correlation (DIC) method was applied in this experiment. The specimens have a thickness of 0.131mm and the ratio of external diameter (R_0) to thickness (H) R_0/H is 252. Due to its curved and thin walled elements, measurement of displacement and strains by using the traditional methods is difficult, because there is not enough space for sticking necessary torsion gauges to measure the out-of-plane behaviour, even if it is possible, the rigidity of the gauge itself will have an effect on the buckling strength. However, by using the optical image correlation method, the problem is solved. DIC method is an optical instrument which utilizes the full-field and non-contact measurement to gauge the three-dimensional displacement and strains on materials and structural parts. In this paper three dimensional digital image correlation system is applied to observe the buckling generation process in details and make a record of the surface displacement during the compression test by using two high resolution digital cameras, then the test data are analyzed and compared by a special correlation technique which can determine the surface displacements of cylindrical shells and it is shown in colour contour in full-field region. The buckling strengths obtained by the theoretical and experimental methods are compared and discussed in this paper. The experimental study shows that the buckling strength of theoretical value is much higher than that of experimental one, because the buckling strength is highly dependent on the imperfections.

Keywords: Digital image correlation method, Buckling, Thin-walled cylindrical shell, Compression test

1. Introduction

Cylinder shells combine light weight with high strength, they are widely used in the most diverse branches of civil engineering technologies, such as pipelines, aerospace, shell roofs, liquid-retaining structures and petrol tanks. S.Aghajari and H. Showkati (2006). As to this kind of structure, the governing failure mode is frequently buckling under axial compression. A lot of research has been undertaken on the buckling strength of this kind of structures. NASA (1968); J. Singer and R.T. Haftka (1975); A.N. Kounadis (2006). Many researches were done on theoretical solution of the elastic buckling due to the axial compression of the cylindrical shell, which is located as basic problem of buckling of the shell. The theoretical analysis finished by S.P. Timoshenko (1961) was one of the most representatives. N. Yamaki (1984) also did some theoretical analysis on this item. It was also compared with the classical theory of Timoshenko. The elastoplasticity buckling valuation was also proposed by NASA: SP.8007 and ASME: Boiler and Pressure Vessel Code Case N-284. Recently experimental studies also show that the buckling strength of theoretical value is much higher than experimental one, S.R. Li and R.C. Batra (2006). Buckling experiment of cylindrical shell requires advanced experimental technology, due to its curved and thin walled elements, measurement of displacement and strains using the traditional methods are difficult. The traditional measurement for distortion value is to use deformation gauge. But the value obtained by the gauge is just an average one along the length of stuck area. For the buckling deformation it is necessary to stick many distortion gauges, even if it is possible to stick so

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many gauges, there must be a great influence caused by those gauges because the structure itself is thin-walled.

In this paper 3D digital image correlation system is applied to observe the buckling generation process in details during the compression test of a thin-wall cylinder shell. Theoretical and experimental values of buckling strength are compared, the discrepancy between them are also discussed.

2. Digital Image Correlation Method

The 3D Digital Image Correlation (DIC) method is an optical instrument for full-field, non-contact and three dimensional measurement of deformations and strains on structural elements and engineering materials. The system uses two high resolution digital cameras to record surface changes of the specimen as it deforms. The recorded images are analyzed and compared by a special correlation technique which allows the determination of the object contour as well as the surface displacements with high local resolution.

2.1. Introduction of Digital Image Correlation System

The DIC method has been developed and used to measure deformation and strains of materials under various loading regimes with sub-pixel accuracy since the 1980's. It has been successfully applied to determine strains in specimens of solid. The method allows determination of displacements of selected points of the mesh on the surface of the deformed specimen by comparing successive images acquired during a test and cross correlating the gray intensity patterns of the direct neighborhood of the points (or the reference areas). In-plane strain values ε_x, ε_y and γ_{xy} for deformation of specimen surfaces may then be obtained from analysis based on a triangular or rectangular network of points L.Muszynski et al. (2000). In addition, out of plane displacements may be accurately measured if two cameras are arranged in front of the same specimen area at an angle so that the displacements captured at the same instants of time by two cameras are correlated to provide stereoscopic information (Figure 1). Such capability is provided by the ARAMIS system by GOM, MbH, P.Alan et al. (2004), and has been successfully applied to a wide range of experimental problems. Detailed description of the 3-D measurement principles, system specifications, calibration procedures, and sample applications are given by H.A.Bruck et al. (1998), W.Ranson et al. (1987) and G.Vendroux et al. (1998).

The system is consisted of three parts as follows (Figure 1):

(1)2 black and white digital cameras (1600 × 1200 pixels) for catching speckle images.

(2)PC for presenting and analyzing the displacement and strain fields.

(3)Matching program (Vic-Snap) for presenting and analyzing the speckle images.

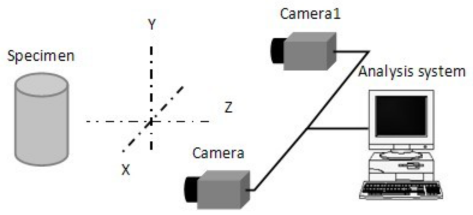

Figure 1 Schematic diagram of DIC system

2.2. Measurement accuracy of Digital Image Correlation System

In order to investigate the measurement accuracy, tension test was carried out on aluminum alloy specimens. Strains were measured by both of the digital image correlation method and traditional strain gauge. The results are compared and shown in Figure 2:

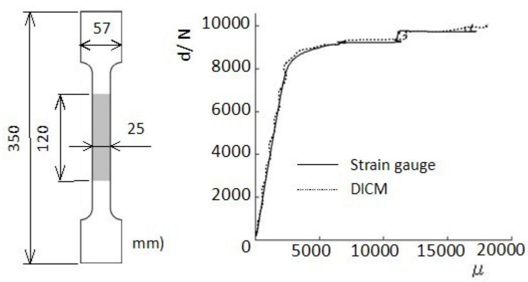

Figure 2 Strain measurement by using gauge and DIC method

Moreover by using this system, the dimension of cylindrical shell samples is determined and compared with the one measured by the micrometer. The results are shown in Figure 3 and Table.1, from which it can be noted the inaccuracy is less than 0.03%.

3. Experimental set up

Specimens are cleaned with a degreaser. A white (or black) base paint is sprayed on the surface of the

Table 1 External diameter of the specimen (mm)

Micrometer	DIC method	Inaccuracy
33.00	32.99	0.03%

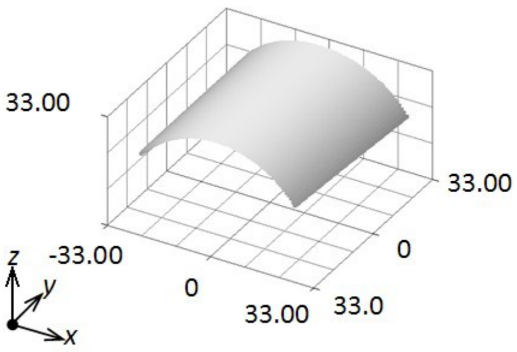

Figure 3 Dimension of cylindrical shell measured by DIC method

specimen to form a thin uniform background. After the base color is dried, a speckle pattern of black (or white) is sprayed on the same face to form a random pattern covering approximately 50% of the face. The speckles should be of the same size as the speckles in the calibration plate used during calibration of the system, which is discussed in more detail later in the paper.

The two cameras are calibrated through a step-by-step procedure. A calibration plate used in the procedure has a pattern of black dots on a white background that are equally spaced and have the same diameter. Different sizes of calibration plates can be used depending on the size of the specimen's Region of Interest (ROI). During the calibration procedure, the plate is moved toward the cameras, away from the cameras, tilted, and rotated through about 15 steps. This process provides the software with enough information to calibrate a volume of a cubic shape having the face dimension as the size of the calibration plate. The ROI should be inside this volume for the system to compute strains and displacements. Once the system is calibrated, a mechanical test is conducted while the system snaps images at a given frequency in this research which is 1.0Hz. The frequency at which the system captures images depends on the specified number of data points during loading of the specimen. Selecting the right frequency is a compromise between the number of data points and computational time.

Analysis input parameters in digital image correlation system, which may be easily adjusted to the particular experimental setup, are: facet size, facet step and calculation base or the size of the strain computation matrix. Increasing facet size may improve the precision of point recognition (or determination of an individual facet displacement) without affecting the sensitivity to local strain variations. This is done at the expense of calculation time. The precision and local accuracy of the calculated strains may be improved by increasing the facet step. This is done at the expense of sensitivity of local strain variations but with a reduction in the calculation time. The precision and local accuracy may be improved by increasing the calculation base. By default, the strain values for each point of the mesh are calculated from the relative change in position of its 8 neighbors (calculation base=3). This parameter may theoretically be increased to 5 or 7 (24 and 48 neighbors respectively) or as much as it is deemed practical. This is done at the expense of the calculation time and the sensitivity to local strain variation (Figure 4 and Figure 5). The improvement in accuracy stated above is only local and does not improve the global accuracy.

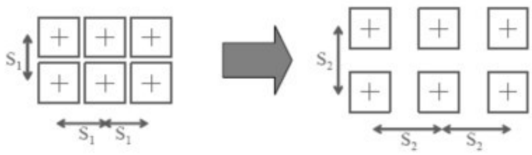

Figure 4 Increase in Facet Step

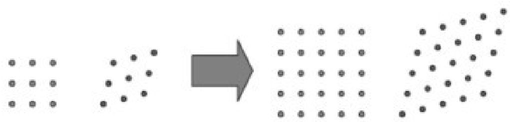

Figure 5 Increase in the Calculation Base

4. Experimental results

4.1. Visualization of the Buckling Phenomena

Two types of Cylinder shells were employed in this experiment, details are listed in Table.2. In which Z is the shape factor of the samples and it was given by Equation (1) as follows:

$$z = \frac{\sqrt{1-\nu^2} \times L^2}{RH} \quad (1)$$

Both of the upper and lower boundaries of the specimens were fixed in the loading plate by using silica gel (Figure 7(a)). One of the key points is making sure that the loading plate is horizontal. During the loading process, the optical system took pictures at a certain frequency of 1 Hz, so that the surface displacement of the shell specimen can be recorded.

Table 2 Parameters of specimens.

Type	Internal R/mm	External R_0/mm	Thickness H/mm	R/H	Length L/mm	L/R_0
I	32.935	33.000	0.131	252	66.0	2.0
II	32.935	33.000	0.131	252	99.0	3.0

Figure 6 is the Loading-Displacement curve, in which the peak point and sudden drop in the load due to the buckling failure of the specimen are marked by point 1 and 2. The buckling phenomenon of the thin-walled cylindrical shell is described by both of the picture which was taken by normal digital camera in Figure 7(a) and the contour figure which was produced by DIC system in Figure 7(b).

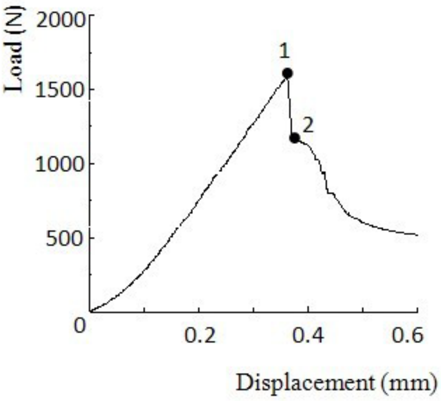

Figure 6 Load and Displacement curve

Typical full-field strain patterns from the compression test of two types on cylindrical shells are shown in Figures 8 and 9. Local strain variations in the specimens were observed. By using this strain contour diamond buckling phenomena was measured and visualized. Full field strain information was also obtained and stored in the system, the desire data for further analysis (e.g. graphing) can be easily exported following the prescribed limit.

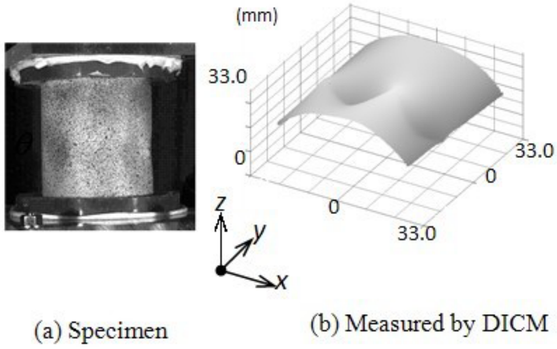

Figure 7 Comparison of Buckling Phenomena Described by normal camera and DIC system

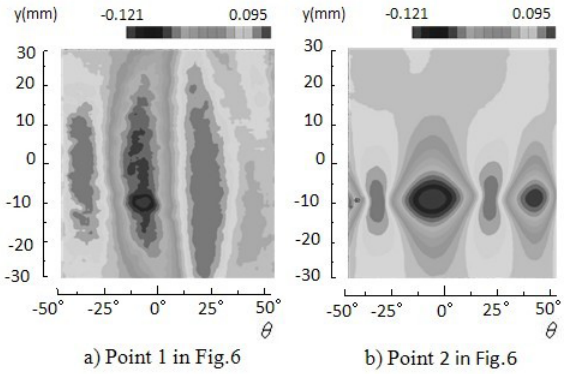

Figure 8 Full-field Longitudinal Strain in Specimens A.

4.2. Buckling Strength

Cylindrical shell structures are subjected to compressive stresses in the direction of the cylinder axis, which can be either uniform or varying throughout the cylinder. The buckling strength of a thin cylindrical shell under axial compression is particularly sensitive to pre-existing imperfections, which can be noted in our test that the buckling strength obtained in this experiment is about 80% of what calculated by NASA (National Aeronautics and Space Administration of USA) minimum equations. Theoretical equation applied for comparison in this paper as given by Equation (2) as mooted by Weingarten et al. (1965).

$$\sigma_{a,cr}^{e} = 0.6E\frac{H}{R}\{1 - 0.901[1 - exp(-\frac{\sqrt{R/H}}{16})]\} \quad (2)$$

Buckling strengths of the theoretical one, experimental one and that calculated by NASA equation are compared and listed in Table.3 as follows:

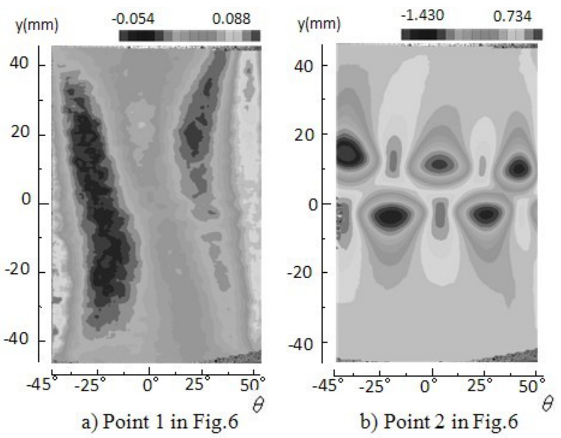

Figure 9 Full-field Longitudinal Strain in Specimens B.

Table 3 Comparison of buckling strength/MPa

Specimens	Theoretical	NASA	Experimental
A	168.5	73.1	58.7
B	168.5	73.1	60.0

Therefore the imperfections can be the main reason for inaccuracy of the buckling strength, loading and boundary conditions can also make the axially compressed cylinder a classical exemplar for behaviours that may be found in a less marked form in this research.

5. Conclusions and Discussions

The potential of visualization of buckling behaviour on thin-walled cylindrical shell by using digital image correlation techniques as a kind of full-field non-contact strain measurements was demonstrated.

Typical full-field strain patterns from the buckling tests are obtained as shown in Figures 8 and 9. Local strain variations in the specimens, which are measured without any influence on the rigidity by the non-contact measurement, are observed. The measured surface strain fields are averaged in the region of interest to compute properties of the materials, so that not only the full-field strain can be obtained, but also the stress parameters can be calculated if necessary. This Digital Image Correlation method procedure results in mean strain values that are not affected by local strain variations, which is an advantage compared to conventional resistive strain gages.

As to the thin-walled cylindrical shell under axial compression, the buckling strength is particularly sensitive to imperfection, loading conditions and boundary conditions. In present experiments the inaccuracy caused by them is about 20%, which is not an acceptable value. For these reasons, the axially compressed cylinder especially with less imperfection has probably been the most extensively studied of all shell buckling behaviours, giving a wealth of evidences from both experimental and theoretical work.

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