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DEVELOPMENT OF OPTICAL-DIGITAL METHODS FOR NON-DESTRUCTIVE TESTING OF AEROSPACE THIN-WALLED SHELL STRUCTURES (REVIEW)

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ABSTRACT

A series of studies on diagnostics and non-destructive testing of the stress-strain state of thin-walled cylindrical shell structures of aerospace engineering by optical-digital methods, in particular, three-dimensional (3D) digital image correlation (DIC) and laser photogrammetry methods, are described. The effectiveness and continuous improvement of these methods over the past decades has been noted. The results of experimental studies of composite and metal shell structures using the methods of 3D DIC are considered. The advantages of 3D DIC methods for simultaneous measurements of surface displacement and deformation fields using several digital image correlators located around the shell structure, over those 3D or 2D DIC methods that provide simultaneous registration of only a local area of the investigated surface using one correlator, were analyzed. The effectiveness of these methods for non-destructive testing of the dynamics of changes in the processes of the surface deformation and destruction under axial and radial loads, as well as for evaluating the knockdown factor of the thin-walled shell structure, is shown

KEYWORDS: shell structure, 3D digital image correlation, digital image correlator, composite cylindrical shell, metal cylindrical shell, knockdown factor, axial loads, radial loads

INTRODUCTION

Diagnostics and non-destructive testing of the stress-strain state of cylindrical shell structures is an important link in the entire process of building flying vehicles of aerospace engineering. One of the main ideas of these studies consists in the evaluation of the knockdown factor (KF) of a shell, which is determined as the ratio of critical load of a real cylinder, which leads to its buckling during longitudinal bending, to critical load of an ideal cylinder, as well as selecting optimal methods to increase KF.

Experimental studies of mechanical characteristics of thin-walled shells of space aircraft fuel tanks under the action of dynamic and static axial loads were carried out within the NASA space projects starting from the 50s of the 20th century. In particular, methodological NASA SP-8007 recommendations were worked out for the preliminary design of thin and moderately thick cylindrical shells under the action of axial compressive loads [1]. In the recommendations, it was proposed to evaluate the stability of a real cylinder using KF.

The mentioned recommendations initiated a series of experiments with composite and metal cylindrical shells, during which optical-digital methods were used to evaluate the geometric parameters of shells under the action of axial and other types of loads on them. In particular, the authors [2] studied thin-walled polymer laminated cylindrical shells reinforced with carbon fiber under combined and torsional loads. Laminated composite cylinders of the Z-series with a height of 510 mm, a radius of 250 mm and a thickness of 1.25 mm (thickness of each layer was 0.125 mm, orientation of the fibers of each layer differed from the orientation of the fibers of the adjacent layers) were manufactured at the Institute of Composite Structures and Adaptive Systems (ICSAS) of the German Aerospace Center [3, 4]. To evaluate the geometric parameters of nine composite cylinders (Z18, Z23, Z25, Z28–Z33), photogrammetric measurements were performed before applying loads, and at the moment of applying axial loads, non-destructive testing of transverse deflections of cylindrical walls caused by longitudinal bending was carried out using the design method of moiré fringes [2]. The conducted experiments showed that the eccentricity in the strength distribution of a shell has a great influence on the value of axial bending load, and this effect is weakened at combined loads.

At the beginning of the 21st century, the methodological NASA SP-8007 recommendations no longer took into account the potential of new materials, in particular, their mechanical and physical characteristics. The obtained differences between theoretical and experimentally obtained KF were quite significant [5–9]. As a result, numerous studies ended in a large range of KF, which was explained by many factors, in particular, imperfections of real shell structures (local defects, bends, pits, damages to layers in the composite, etc.) [6, 9]. At the same time, the main attention was paid to axial loads, while radial (transverse) loads were practically not taken into account [10]. In addition, the existing methods and means were unable to control the entire process of changing the stress-strain state of the surface of shell structures from the beginning of applying loads to them until their complete destruction. The searches for new high-speed approaches to studies of displacement fields and surface deformations of shell structures throughout the whole field simultaneously led to the introduction into practice of experimental studies of hybrid optical-digital methods of registration, processing and analysis of large two- and three-dimensional information arrays, in particular, methods of digital image correlation (DIC).

APPLICATION OF DIC FOR NON-DESTRUCTIVE TESTING OF SHELL STRUCTURES

In recent years, researchers have paid special attention to improving the technical characteristics of shell structures, reducing their weight and cost, which ultimately leads to an increase in KF. One of the key factors in achieving high KF values was the use of optical-digital methods and systems of non-destructive testing of experimental and real shell structures of rocket and space engineering. Among them, the methods of three-dimensional (3D) DIC began to play a particularly important role, since with their help it is possible to restore a complete pattern of surface displacements and deformations simultaneously over the whole shell during its loading. At the same time, the experiments performed by such methods were combined with computer simulation, in particular with finite element methods (FEM), which take into account various imperfections of shells. The results of such complex studies made it possible to calculate KF for different types of shell structures.

The effectiveness of using DIC during loads of shell structures is predetermined, first of all, by the possibility of registering large areas of the surface of the research object in real time and the ability to ensure high accuracy of forming the fields of normal and tangential surface displacements and deformations. Due to the use of high-performance algorithms for surface image processing, it is possible to achieve such an error in calculating the restored field of displacements, which is comparable to 0.01 pixels in a matrix video sensor of a digital camera [11]. DIC is based on the correlation comparison of intensity distributions of speckle patterns of optically rough surfaces, diffuse media, or images of smooth surfaces with randomly placed spots applied by dye spraying or obtained by other methods. In DIC, only the intensity of the light field is a carrier of information, and the loss of phase information is compensated by a wider range of measuring surface displacements and deformations compared to digital speckle interferometry, shearography and digital holography. The formation of fields of displacements or deformations using DIC is performed by the correlation comparison of the $(m, n)^{\text{th}}$ fragment of an image of a deformed surface with the corresponding $(m, n)^{\text{th}}$ fragment of an image of the same surface, which is in the preliminary or initial state. For this purpose, two images are recorded with a digital camera, after which they are split in the computer into $M \times N$ of square or rectangular fragments containing an odd or even number of pixels, for example 15×15; 16×16; 31×31; 64×64 etc. Distinguished are two-dimensional (2D) DIC, in which the fields of in-plane (tangential) displacements and deformations are determined, and 3D DIC, in which the three-dimensional fields of displacements and deformations are determined, i.e. both in-plane and out-of-plane at the same time. Thousands of scientific papers have been devoted to 2D and 3D DIC methods and their use in various applied studies. For an in-depth study of these methods, it can be referred, for example, to [11–18].

There are several approaches to the formation of 3D fields of displacements and deformations of research objects using DIC methods. Among them, the most common belongs to M. Sutton's group [14, 19], according to which the same area of the surface is registered by two digital cameras from two points in space and, using the stereoscopic effect, all three orthogonal components of displacements are measured. They also developed the method of angular displacements [19], where the optical axes of two cameras are intersected on the research object. The method is quite flexible and is implemented using a simple optical system. However, here a larger part of the research object is outside the depth of field of projection lenses, which leads to the distorted image of its surface due to defocusing of a part of this image. To get rid of such defocusing, the Scheimpflug condition [20] is used, which improves the image, although it does not completely eliminate geometric distortions. The works of M. Sutton's group became the basis for the creation of optical-digital systems (ODS) of 2D and 3D DIC, i.e., digital image correlators, including the corresponding software. Among them, the non-contact 3D digital image correlation ARAMIS systems (produced by Trilion Quality Systems) [21] can be distinguished, which, in combination with VIC-3D software [22], make it possible to restore the fields of dynamic displacements and surface deformations of various objects during their loading.

DIC methods also make it possible to measure deformations of the 360° surface area of cylindrical shell structures that have a relatively large curvature. There are two main approaches to remote monitoring of such structures:

1. Simultaneous measurements of fields of displacements and surface deformations using several 3D digital image correlators located around the shell or in the area where destruction of a shell is most probable;

2. Measurements of surface fields of displacements and deformations using only one 3D or 2D digital image correlator, which registers either a series of speckle patterns of a cylindrical surface during its rotation, or a part of the surface that it covers.

The first approach was used in most of the works devoted to this topic, as it provides a synchronous registration of surface displacements and deformations over the 360° area of a shell and is fast. Moreover, the frame rate can be changed in a wide range depending on the experimental conditions. The second approach requires much less material costs, however, it is less effective, as it provides a simultaneous covering only of a part of the entire surface of the shell structure [23–27]. Sometimes it is applied in combination with the first approach and using several digital correlators for a more accurate analysis of a selected surface area containing local imperfections and defects [5, 6].

NON-DESTRUCTIVE TESTING OF COMPOSITE SHELL STRUCTURES OF AEROSPACE ENGINEERING

Most likely, 3D DIC was for the first time used to study loads on shell structures for rocket and space applications in [5], and the obtained results were supplemented in [6]. The main goal was to establish a more realistic lower bound descending exponential dependence of KDF on the ratio of the radius R of a cylindrical shell to its thickness t, i.e., on R/t, which would exceed the same traditional dependences [25, 28, 29] or dependences of KDF on the Batdorf parameter [7–9]. Six polymer laminated cylindrical shells Z07–Z12 reinforced with carbon fibers, with a heigth of 510 mm and a radius of 250 mm, manufactured at the ICSAS, were used for the experiments [30]. The cylinders contained four layers of 0.125 mm thickness with different fiber orientations; the total thickness of the cylinders was 0.5 mm. To assess the quality of the produced internal and external surfaces of the cylinders before applying loads, including to detect technological local damages, imperfections and defects, non-destructive testing was carried out by ultrasonic pulse-echo and photogrammetric methods. At the same time, delaminations were detected by the pulse-echo method, and surface inhomogeneities — by photogrammetry with the use of the ATOS measuring system [31]. Axial compressive loads were applied to cylindrical specimens using a hydraulic machine designed for axial compression of specimens [32]. Measurements of 3D fields of deformations during static and dynamic loads of shells were carried out using four 3D digital correlation ARAMIS systems [21]. Each system contains two high-speed digital cameras with the sizes of 1280×1024 pixels and the maximum frame rate of 920 Hz, which register approximately 100° of the shell surface segment, and four systems cover all 360° of the surface (Figure 1). Deformations of shells were determined by the displacements of their surfaces relative to the initial state before applying loads. To achieve rapid registration of local dynamic fields of surface displacements during its deformation, all four ARAMIS systems were placed in the selected area of the Z07 cylinder, where its destruction is most probable, covering a height of 450 mm and a field of view angle of ~40° (Figure 2), and recorded this area at a rate of 3680 Hz. It is shown that surface deformations at a dynamic load start from the location of the point bend in the center of the area, are accompanied by variable patterns of displacement field during longitudinal bend and end in a stable pattern of displacement field after buckling of a cylinder area. Here, also the procedure of non-destructive testing of the surface and internal layers of cylinders were considered before applying loads in order to detect technological local damages, imperfections and defects. Testing was carried out by a pulse-echo method as well as by a photogrammetric method using ODS ATOS [31].

Two sequences of displacement distributions for the same cylinder in unloaded and loaded states were obtained by authors of [30] using four ARAMIS systems over the whole shell area. The similar studies with the specimens of four-layer composite cylindrical shells Z15U500, Z17U500, Z18U500, Z20U500 and Z22U500 (height of 500 mm, radius of 250 mm, thickness of 0.5 mm, orientation of layers [+24°/–24°/+41°/–41°] were described in [33].

A work [10] has become a logical continuation of non-destructive tests of cylindrical shells produced at the ICSAS using ODS. Two test cylindrical specimens Z36 and Z37 of laminated carbon plastic composite, reinforced with carbon fiber (sequence of laying layers is [34/–34/0/0/53/–53]), of 800 mm height, 400 mm radius and 0.75 mm thickness were investigated, by applying axial compression and transverse (radial) loads on them. The axial compression was performed with the help of specially manufactured test equipment, and transverse loads — with the help

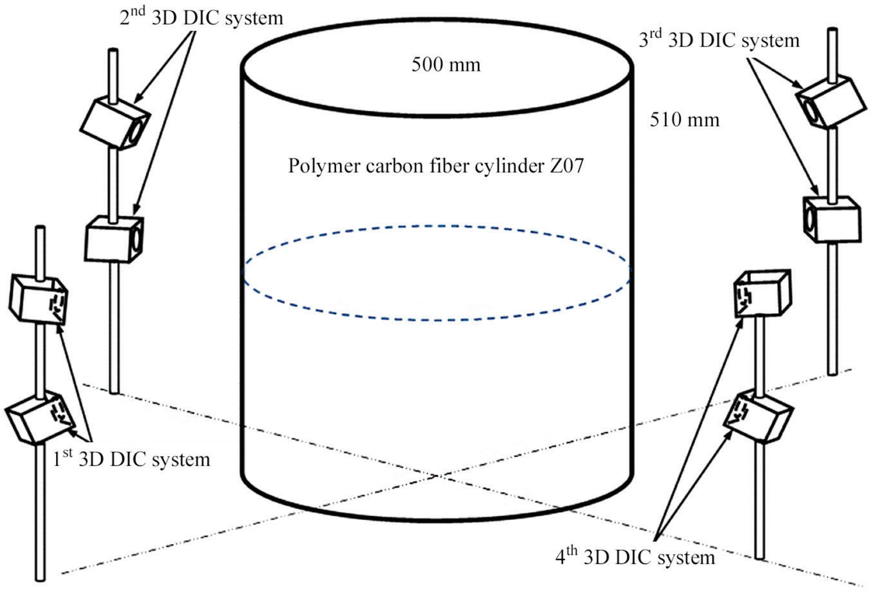

Figure 1. Simultaneous registration of 3D deformation fields of the entire outer surface of the cylinder during its static and dynamic loads with the use of four 3D DIC ARAMIS sytems

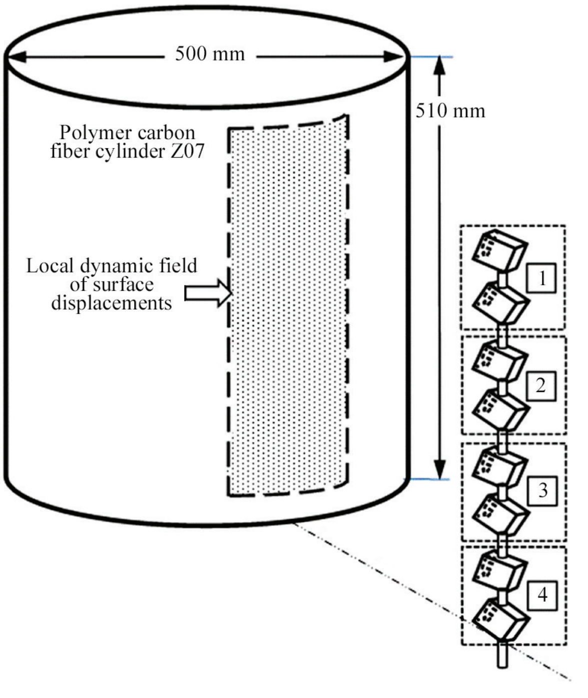

Figure 2. Simultaneous high-speed registration of the local field of surface displacements (angle of view is ~40°) during static and dynamic loads of the cylinder with the help of four 3D DIC ARAMIS systems: 1 — first system; 2 — second system; 3 — third system; 4 — fourth system

of a device containing magnets, operating in the radial direction. First, a constant transverse load, and then a monotonous growing compression load were applied. Transverse loads of 0–20 N were applied in three radial directions at angles of 30°, 150° and 210° for the specimen Z36 and at an angle of 30° for the specimen Z37. With the help of a scanning photogrammetric ATOS system, the initial geometric imperfections in the test cylinders were allocated, including surface and internal defects and damages, using the best-fit procedure (optimal approximation) to eliminate the displacement of a solid body from the results of measurements [34]. The fields of spatial deformations of the cylinder surface were determined by means of strain gauges. In addition to strain gauges, the 3D correlation ARAMIS Adjustable 12M system was also used [35] to study the spatial deformations of the surface. For this purpose, a spotty structure was deposited to the surface of the cylinder to simulate speckle pattern at the input of two digital cameras of the system. The obtained fields of displacements made it possible to detect surface depressions, convexes, pits and other deviations from the ideal cylindricality during compression of test cylinders both before and after the appearance of a longitudinal bending of the specimens. In parallel with the experiments, FEM based on Abaqus Standard 6.14 (Implicit) software was used. By means of FEM, the dependencies between the axial load of longitudinal bend and the transverse disturbing load for the ideal model of a cylinder and the model of a cylinder with internal imperfections, including places with deviations of layer thickness and with changes in the volumetric fraction of carbon fibers were determined. It is shown that the results of calculating the spatial distribution of displacements of the surface of the cylinder model with the introduced imperfections are quite well correlated with the results of experiments with Z36 specimen performed using the ATOS scanner and the ultrasonic broadband scanner.

Due to the need in reducing the weight of structural elements of the aircraft engineering, the problem of manufacturing adapters of useful load and intermediate stages of a launch vehicle from composite materials is quite relevant. To solve the problem, in [36] it is proposed to use the methodology of FEM to predict the behavior of a shell structure during its longitudinal bend and compare the results of simulation with experimental data, obtained with the 3D digital correlation systems and strain gauges located on the cylinder surface. To simulate the real sizes of cylindrical shells of aerospace engineering, a new analytical scaling methodology was proposed. The methodology was used to design a composite cylinder of a reduced size, which has the same characteristics during buckling as a full-size multilayered composite cylinder. Such designing included, first and foremost, comparison of the dimensionless parameters of a scaled structure with a full-scale one [37]. Based on the results of designing, an experimental cylinder NDL-1 was produced of layers of a carbon fiber, joined by an epoxy material of 800 mm diameter, 1200 mm height and with a sequence of laying the composite layers [23/0/–23]. The NDL-1 design was a reduced version of a multilayered composite cylinder CTA8.1 with a diameter of 2.4 m, which was designed and tested as a part of the NASA SBKF project (Shell Buckling Knockdown Factor) [38]. Non-destructive testing of the experimental cylinder NDL-1 was carried out by the methods and means of photogrammetry and 3D DIC. To evaluate the available imperfections and deviations from cylindricality before applying axial loads to the experimental specimen NDL-1, optical scanning of the internal and outer surfaces was performed by the photogrammetric method. During the experiments, at the NASA Research Center in Langley, Virginia, surface displacements and deformations were measured by the system of strain gauges attached to the cylinder and 3D digital image correlators. In order to register artificial speckle patterns by the 3D DIC method, black ovals and circles of 4.5–6.0 mm were randomly applied to the light-coloured surface of the cylinder. Axial compressive loads of up to 3000 kN were performed using a specially designed test load installation. At the initial stage of the experiment, four 3D DIC systems were used with a slow rate of registering speckle patterns, which is equal to 1 frame/s. The cameras were placed at angles of 90° relative to each other. With an increase in the compressive axial load during the development of the longitudinal bending process and until buckling of the cylinder, four high-speed 3D DIC systems were used, the rate of registering speckle patterns in which was 20,000 frames/s. The comparative analysis of deformations of the cylinder surface during loads obtained on the one hand by 3D DIC systems, and on the other by means of FEM using ABAQUS 2017 product showed a satisfactory convergence of the experimental and simulation data. In particular, at the initial stage, axial loads calculated by FEM, differ from experimental ones by 0.04 %, and the estimated stiffness ratio by 1 % from the measured experimental one. However, the difference between these data increased during the longitudinal bending of the cylinder material. The behavior of the surface after buckling during the experiment was similar to its behavior. However, damages during longitudinal bending and after buckling that were registered experimentally, were not taken into account in FEM, which led to differences between the simulation and experimental data. The obtained results showed the possibility of using the method of studying full-scale cylindrical shell structures proposed by authors.

NON-DESTRUCTIVE TESTING OF METAL SHELL STRUCTURES OF AIRCRAFT ENGINEERING

In parallel with composite shell structures, metal ones made of aluminium alloys were also investigated. Starting from 2011, in NASA within the frames of designing and creation of a super-heavy launch vehicle Space Launch System (SLS) for a manned spacecraft, the research program was fulfilled to improve the KF evaluation procedures for full-scale specimens of metal shell structures made of aluminium alloys [39]. In particular, Correlated Solutions, Inc. submitted information on its website regarding a successful test of a full-scale cylindrical experimental specimen with a diameter of 27.5 feet (8.38 m) and 242 in (6.15 m) made of Al–Li 2195 alloy, in March 2011 at the NASA Marshall Space Flight Center [40]. The specimen simulated the SLS fuel tank and was an analogous to the external fuel tank of a spacecraft Space Shuttle. Generating of displacement and deformation fields of the entire surface while applying axial, radial and other types of loads, was carried out with the help of 3D digital image correlators together with the VIC-3D software, developed and produced at the Correlated Solutions, Inc. On the outer white surface of the specimen, randomly distributed black ovals and circles of preset sizes that simulated a speckle structure were applied. In the experiment, seven 3D digital image correlators were used that covered the entire surface from 0 to 360° and tested it almost continuously. The specimen was gradually loaded up to more than 800,000 lbs, and the 3D DIC digital cameras registered the displacement fields at a rate of 3000 frames/s until the cylinder was completely destroyed.

More comprehensive information on the results of further studies with the full-scale cylindrical specimens and with the specimens of a smaller scale at the NASA Marshall Space Flight Center is reflected in [41, 42]. Data on the creation of two metal full-scale 27.5-foot test cylindrical shells and a deep study of their behavior during application of axial compressive loads, combined loads and internal pressure of the order of 1 psi (6895 Pa) is given in [41]. Here, the authors report about the designing and creation of eight small-scale cylinders with a diameter of 8 feet (2.44 m) and 6.5 feet (1.98 m) height, as well as two full-scale ETTA1 and ETTA2 cylinders. All of them were made of Al–Li 2195 alloy. ETTA1 and ETTA2 cylinders consisted of eight panels, welded between each other along the axial direction by the method of friction with stirring. The panels contained reinforced stiffened areas, weld zones and transitional areas between the weld zones and reinforced areas. ETTA1 was designed to evaluate the process of buckling under the action of axial uniform compression and therefore the panels in it had a low reinforcement. ETTA2 was designed to evaluate the same process for combined compression and bending loading. Therefore, it contained both panels presented in ETTA1 and much rigid panels.

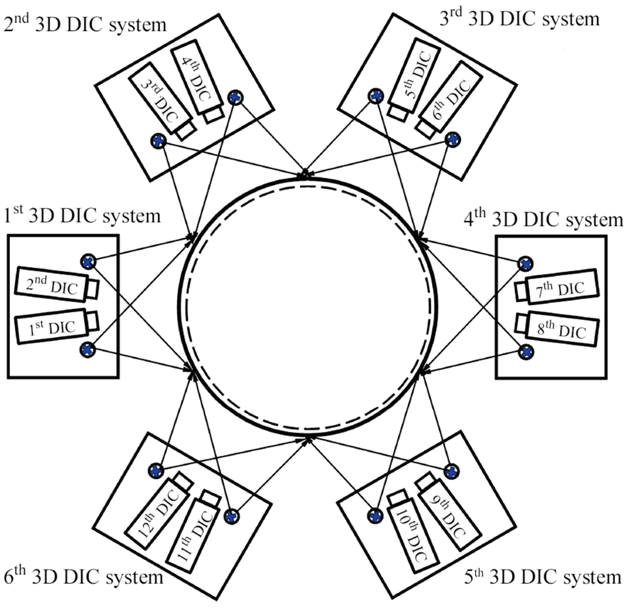

Figure 3. Scheme of experimental equipment for testing a metal full-scale cylinder containing six 3D DIC systems, each of which contains two digital cameras (DC) and two sources for illumination of the registered surface area

During the tests of full-scale cylinders, sensors of linear displacements, strain gauges, pressure sensors, photo/video systems and 3D DIC systems were used. 842 strain gauges were attached to ETTA1 and 1168 strain gauges were attached to ETTA2. Three-dimensional displacement and deformation fields of the outer surface were measured using six 3D DIC high-speed systems located round a circle around the cylinders (Figure 3). The systems monitored the transitional processes of a longitudinal bend of the surface and buckling of cylinders during their loads. For spatial referencing of these systems on the cylinders surface, markers in the form of a letter *L* were applied on the cylinder surface, which was formed with the help of a set of randomly distributed black squares that had approximately the same sizes as black circles and ovals on the white surface of the specimens. 3D DIC systems also measured local displacements and deformations between the markers pairs. The results of measurements with the help of these systems made it possible to evaluate the effect of local bending of elements of the outer lining of the cylinder and welds on the process of buckling of ETTA1 and ETTA2 cylinders. In particular, it is shown that the bend and groove of the lining adjacent to the axial welds in the specimens leads to the nonlinear reaction of loading on the axial deformation at lower levels of loading than it was supposed.

The work [42] shows the results of studies of two small-scale 8-ft test cylindrical shells TA07 and ITA02, made of Al–Li 2195 alloy. Each such cylinder contained three 120° arc segments welded with each other by friction with stirring. The configuration of stiffening elements was chosen on the basis of the NASA launch vehicle cylinder from the Ares 1 acceleration unit. For the multichannel testing, the data of displacements and deformations of the load surface, sensors of linear displacements and strain gauges were used. However, the main attention was paid to restoring three-dimensional displacement and deformation fields of the surface, which was measured with four two-camera 3D DIC. This system contained eight cameras and eight light radiation sources located around the cylindrical shells. Digital cameras with the sizes of matrix video sensors of 2448×2048 pixels were located at angles of 45° relative to each other, which made it possible to cover the surface of the cylinder around the entire circle. To simulate speckle patterns, chaotically arranged black oval spots with the sizes of 0.45–0.70 in (1.14–1.78 cm) were applied to the white surface of the cylinders. The spot sizes were calculated taking into account the spatial resolution of the cameras. The frequency of image registration was 0.2 Hz. The obtained images were processed using the VIC-3D software developed in the Correlated Solutions, Inc. The largest errors of measured displacements of the cylinder surface were observed near their edges, and the smallest — along the central line round a circle of each cylinder, where the correlation between the installed 3D DIC was maximum. The results of measurements of 3D displacements of the surface of two 8-foot cylinders made it possible to upgrade the process of simulating loads of cylinders using FEM and thereby improving the forecasting of the phenomena of their buckling.

The similar studies with metal shells of smaller sizes were performed at the NASA Langley Research Center (Hampton, Virginia) [43, 44]. In [43], 3D DIC were used to determine the fields of displacements and deformations of surfaces of metal cylindrical shell structures. Round cylinders of 31 in length (0.7874 m), 9 in radius (0.2286 m) and 0.04 in thickness (0.102 cm) were manufactured of aluminium 2024 alloy. The tests were performed under the axial compression load and lateral disturbing load, which were applied in the radial direction in the middle of the cylinder length. To capture a complete pattern of displacement field over the entire cylindrical shell area during loads, three 3D DIC were used. To evaluate the test digital models of cylinder surface with an initial unloaded state and during axial and radial transverse loads, analysis using FEM and software Abaqus Standard and Abaqus Explicit products was performed. Simulation results and experimental data obtained by the 3D DIC method, performed during axial and transverse loads, showed some consistency between the restored axial and radial displacement fields, although FEM calculations of predicted local and global critical buckling loads exceeded those measured experimentally.

At the NASA Langley Research Center, a series of experiments with the abovementioned test cylinder TA07 with a diameter of 8 feet (2.44 m) and 6.5 feet (1.98 m) length made of Al–Li 2195 alloy was also conducted [44]. A number of new results were obtained and, in particular, it is shown that the cylinder load expected by FEM was 14.4 % less than that measured by 3D DIC. Four 3D DIC provided both slow registration of displacement field of the entire outer surface of the cylinder from 0° to 360° with a frequency of 0.2 Hz, as well as its rapid registration with a frequency of 5 kHz.

In [24], a cylindrical shell with a diameter of 1 m, height of 0.6 m and thickness of 1.5 mm was made of aluminium 2A14 alloy for evaluation of KF. 36 strain gauges, a laser scanning HandySCAN 3D system for panoramic optical surface measurements, as well as 3D DIC with the VIC-3D software were used to evaluate deformations of the surface under the action of axial loads. Using the HandySCAN 3D system, laser scanning of the cylinder surface before applying axial loads was performed to detect surface heterogeneities. 3D correlator was used to detect the mode structure of the deformed cylinder only after buckling of the cylinder under the action of compressive axial load. At the same time, it was moved six times around the cylinder to measure the shape of the entire surface. In the next work of almost the same author's team [25], four more cylinders of the same size and from the same aluminium 2Al4 alloy were manufactured for research. Here, the main attention was paid to the evaluation of defects and their heterogeneities, which were performed also by 3D DIC. At the same time, it is worth noting that the use of only one 3D DIC did not contribute to the reliable restoring of the displacement field throughout the cylinder surface field and it practically performed auxiliary functions during the experiment.

CONCLUSIONS

Versatile experimental studies conducted by a number of scientists in scientific laboratories and, in particular, at the NASA Langley Marshall Space Flight Center, as well as at the ICSAS of the German Aerospace Center, have shown high efficiency of procedures of construction and measuring surface fields of displacements and deformations and the detection of imperfections in the shell structures of aerospace engineering by means of non-destructive remote optical-digital methods, in particular, 3D DIC methods. The rationality of their use for both composite and metal shells has been shown. 3D DIC systems are ever more intensively used to obtain experimental data on the fields of deformations of shell cylindrical structures during axial compression and radial loads. Moreover, a tendency to increase a number of such systems during the synchronized registration of the cylinder surface is observed in order to increase an accuracy of restoring of all stages of applying such loads up to buckling and destruction of a shell. The use of photogrammetric systems of non-destructive testing of the cylindricity of shell structure surface in an unloaded state in order to identify a variety of imperfections on the inner surface of cylindrical shells was also traditional. A prerequisite for the successful tests of experimental shell structures is a combination of FEM method with optical-digital non-destructive testing methods, in particular, with the 3D DIC method, and establishing a correspondence between the simulation results according to the experiment data.

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