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Quantifying Residual Strains in Specimens Prepared by Additive Layer Manufacturing

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ABSTRACT

Residual stresses and strains are prevalent in many components, especially those that are made using additive layer manufacturing. The residual strains are superposed onto any applied load, which in experimental analysis may lead to inaccurate results. The manufacture of a component with known residual strains in all build orientations will enable it to be tested in its green state with results similar to an annealed counterpart. This study has been conducted to explore the relationship between the orientation build of the component, and its thickness in relation to the amount of residual strain it contains. The samples tested are made using Objet VeroClear, and have an incremental thickness in order to determine the relationship between specimen thickness and residual strain. The test method used is photoelasticity, in which three analytical methods are implemented – Tardy compensation, Null-balance compensation and 6-step phase-stepping. It was established that one of the build orientations possesses no residual strains, and the phase-stepping technique produces the most accurate results. This comparative analysis will aid the development of a simplistic method for manufacturing and testing components with minimal residual strains via additive layer manufacturing. Eliminating the need for post-processing will therefore enable time and cost savings.

Keywords: Additive Layer Manufacturing, Build Specifications, Photoelasticity, Residual Strains

Nomenclature

f_σ	stress optic coefficient
i_n	light intensity
N	fringe order
t	through thickness of specimen (mm)
α	relative retardation
θ	isoclinic angle
σ	principal stress (MPa)
X, Y, Z	global axes of coordinates

Introduction

Additive layer manufacturing is a technique that consists of building a component in layers. It is very useful in industry as it allows for the manufacture of intricate components in a rapid manner and reduces the waste material. Because of its high levels of precision, it is also used to make lattices and meshes for low density components. In addition to this, the same component can be replicated with little effort, as, for some additive manufacturing processes the production machine is only required to read a Computer Aided Design (CAD) file, so larger batches of the same component can be easily manufactured to a high level of accuracy and similarity.

There are many different types of additive manufacturing techniques, depending on the materials used and the form in which the raw materials are. Some of the processes that require a powdered raw material for manufacturing components are: laser sintering – for thermoplastics and elastomers; laser melting – for alloys; and electron beam melting – specifically for non-ferrous alloys [1]. For material deposition processes, wire extrusion and blown powder processes are utilised. However, the most common process is 3D printing, which is widely accessible and relatively simple to use, as the designed component provides the build information via a CAD file. 3-D printing is a quick and effective method of creating complex components with precision, hence its use in this study. The 3-D printing process is suitable for creating prototypes for testing using photoelastic techniques, as some plastics used in the printing process possess birefringent

characteristics. It alleviates the strenuous task of producing intricate moulds and casting, hence allowing for greater accuracy and efficiency in the production and testing of the samples.
Conventionally, when additive manufacturing is used to create components, there is residual strain created in the direction of build due to shrinkage during curing of the material, as shown in a study conducted by Quintana et al [2]. This is not a major deterrent, as relatively simple heat treatment methods allow for the alleviation of these stresses. However, the heat treatment process requires specific apparatus that may be inaccessible to the user. Additionally, most thermoplastics have a degree of sensitivity to moisture absorption from the environment, therefore the characteristics of the sample may change slightly and degradation in material properties could result from excessive exposure to the environment [3]. It is therefore more time efficient and financially lucrative to allow for a procedure that will enable the testing of the component in its green state i.e. directly after build without further post processing, and therefore the aim of this study is to perform a quantitative procedure to determine the specific residual strains within a component that is manufactured via additive manufacturing, and an analysis on build orientation is carried out to inspect the most suitable orientation of build for minimal residual stresses.

Materials and Experimental Methods

The material selected for this study was Objet VeroClear, manufactured by Stratasys Inc. This material is transparent and exhibits birefringence, therefore it is ideal for photoelastic studies. To initialise the manufacturing process, a CAD file is created and loaded into the printer system as a .stl file, which will determine the geometry of the final product. The build layer, which is the thickness of each layer that is used to create the component, is then selected, which dictates the intricacy of the product, hence manufacture duration. The manufacturing process involves layering heated material onto a platform with thicknesses in the order of microns. The head of the printer deposits material as it moves along the platform and once it has completed the layer, it repeats the process layer by layer to eventually create the 3-D model designed in the CAD file.

A specimen was designed to fulfil the following objectives:

1. To investigate the variation of strain with an increase in specimen thickness;
2. To examine the effect that build orientation has on residual strain, with particular interest in obtaining a ‘strain-free’ orientation for simplicity in analysis;
3. To determine the effect of residual strains experienced in the component with respect to the build-up layer;
4. To measure the specimen thickness at which triaxial effects are present, which create distortions and inhibit clarity of results.

The test components viewed as useful for the fulfilment of all these objectives were sets of staircase blocks (fig. 1), which have incremental thicknesses and could incorporate all the information, whilst providing the same build environment, therefore minimising changes and anomalies that can be brought about due to differences in build conditions. The CAD file created contained three different specimens in the three build orientations, where the point of interest regarding the orientation was the through-thickness of the ‘step’. Due to the rigidity of a set build-up layer in the printer prior to manufacture, two batches of the blocks were made consecutively – one with a build-up layer of 16μm and the other with 32μm.

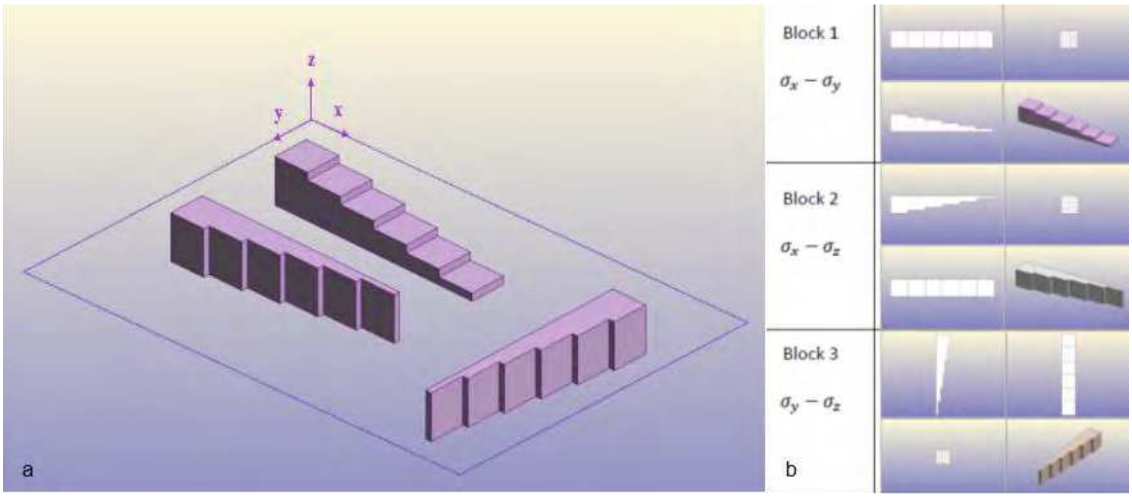

Fig. 1 CAD drawings of the mutually perpendicular staircase blocks with (a) the build orientations specified by the global coordinates x,y and z and (b) the orthogonal drawings to show build variation with respect to the orientations

To gain a measure of the residual strains, photoelastic methods were implemented, as they provide a quick and effective visualisation of the strains experienced within the component. A circular polariscope was used, and this yields isochromatic fringes. The stress optic law (eq.. 1) is then implemented to obtain the principal stress difference ($\sigma_1 - \sigma_2$):

$$\sigma_1 - \sigma_2 = \frac{Nf_\sigma}{t} \qquad (1)$$

where N is the isochromatic fringe order, f_σ the stress optic coefficient and t the through-thickness of the birefringent specimen [4]. Since this is an elastic situation, the strains can be inferred from the stresses. The three main analytical techniques used are Tardy method, Null Balance Compensation and Phase-stepping. These are implemented for comparative studies, in order to validate results and determine the most effective photoelastic method of the three for this particular application.

The Tardy method is the simplest approach, as it only requires the use of the grey-field spectrum of the polariscope. The analyser is rotated by a known angle and a specific point of interest monitored to view the changes in fringe order – this enables fractional fringes to be determined, as the fringe moves by a known distance in the sample, and the rotation gives the angle by which the change has occurred [4]. As this study involved samples with minimal residual stresses, it was found to be more effective to study each 'stair' partition and rotate the analyser to a point at which the fringe appears. For greater simplicity, monochromatic sodium light (**λ**=589.3nm) was used, in order for the specific full fringes to be determined.

Null balance compensation is a quantitative method of obtaining point to point fringe readings within the polariscope [4] using a Null Balance Compensator manufactured by the Vishay Measurements Group. This is an instrument used to establish accurate fringe readings by introducing a variable birefringence with known calibration that is adjusted to cancel out the refractive index of the specimen under observation. This is because the magnitude of birefringence of the null balance compensator and specimen are equal in magnitude, but opposite in direction, resulting in a net birefringence of zero, indicated by a black fringe. The adjustment is carried out using a dial, whose turning gives a specific counter reading and, using the calibration chart that accompanies the compensator, fringe order is easily obtained, with respect to the counter reading. Because there is a linear relationship between the counter reading and fringe order, it is also a simple way of obtaining the fringe order, hence the strains within the component. However, the greatest limitation of this method is the tedious analysis due to a point to point data acquisition, and at very low fringes, there is no clear distinction in the determination of fringe order. It is therefore ideal for initial calibration, but a more robust analytical technique is required to define the holistic strain state of the system.

Phase-stepping is the most appropriate method for studying the specimen, as it gives a full field automated analysis by using images presented by the rotation of both the output quarter wave plate and analyser, which varies the light intensities from the specimen. In this method, there can be up to 8 light intensities used for analysis, making it an over deterministic process, hence reducing the threshold of error. In this particular study, the implementation of the 6 step phase-stepping process developed by Patterson, Ji and Wang [5] is implemented, with the orientations in table (1) yielding simultaneous equations. (2,3) that provided the formulae used to determine the isoclinic angle (θ) and relative retardation (α) from the different light intensities (i_n). Relative retardation is related to fringe order using eq. (4).

Table 1 Orientations for the output elements in the implementation of the 6-step phase-stepping technique developed by Patterson, Ji and Wang: with the equations. yielding the isoclinic angle(2), retardation(3) and fringe order(4) [5].

Intensity	Output $\lambda/4$ plate orientation	Analyser orientation
i_1	0	$\pi/4$
i_2	0	$-\pi/4$
i_3	0	0
i_4	$\pi/4$	$\pi/4$
i_5	$\pi/2$	$\pi/2$
i_6	$3\pi/4$	$3\pi/4$

$$\theta = \frac{1}{2}tan^{-1}\left(\frac{i_5 - i_3}{i_4 - i_6}\right) \qquad (2)$$

$$\alpha = \frac{1}{2}tan^{-1}\left(\frac{i_4 - i_6}{(i_1 - i_2)cos2\theta}\right) \qquad (3)$$

$$\alpha = 2\pi N \qquad (4)$$

Three build orientations are being investigated (fig. 1), therefore the staircase blocks are observed in the plan and side views (figs. 2, 3, 5). This allows the stress differences, as shown in table 2, to be calculated.

Table 2: Nomenclature of blocks for analysis, related to orientation and build layup, as shown in fig. 2

BLOCK NUMBER	DEFINITION
11	16μm build-up layer for block 1 ($\sigma_x - \sigma_y$)
12	16μm build-up layer for block 2 ($\sigma_x - \sigma_z$)
13	16μm build-up layer for block 3 ($\sigma_y - \sigma_z$)
21	32μm build-up layer for block 1 ($\sigma_x - \sigma_y$)
22	32μm build-up layer for block 2 ($\sigma_x - \sigma_z$)
23	32μm build-up layer for block 3 ($\sigma_y - \sigma_z$)

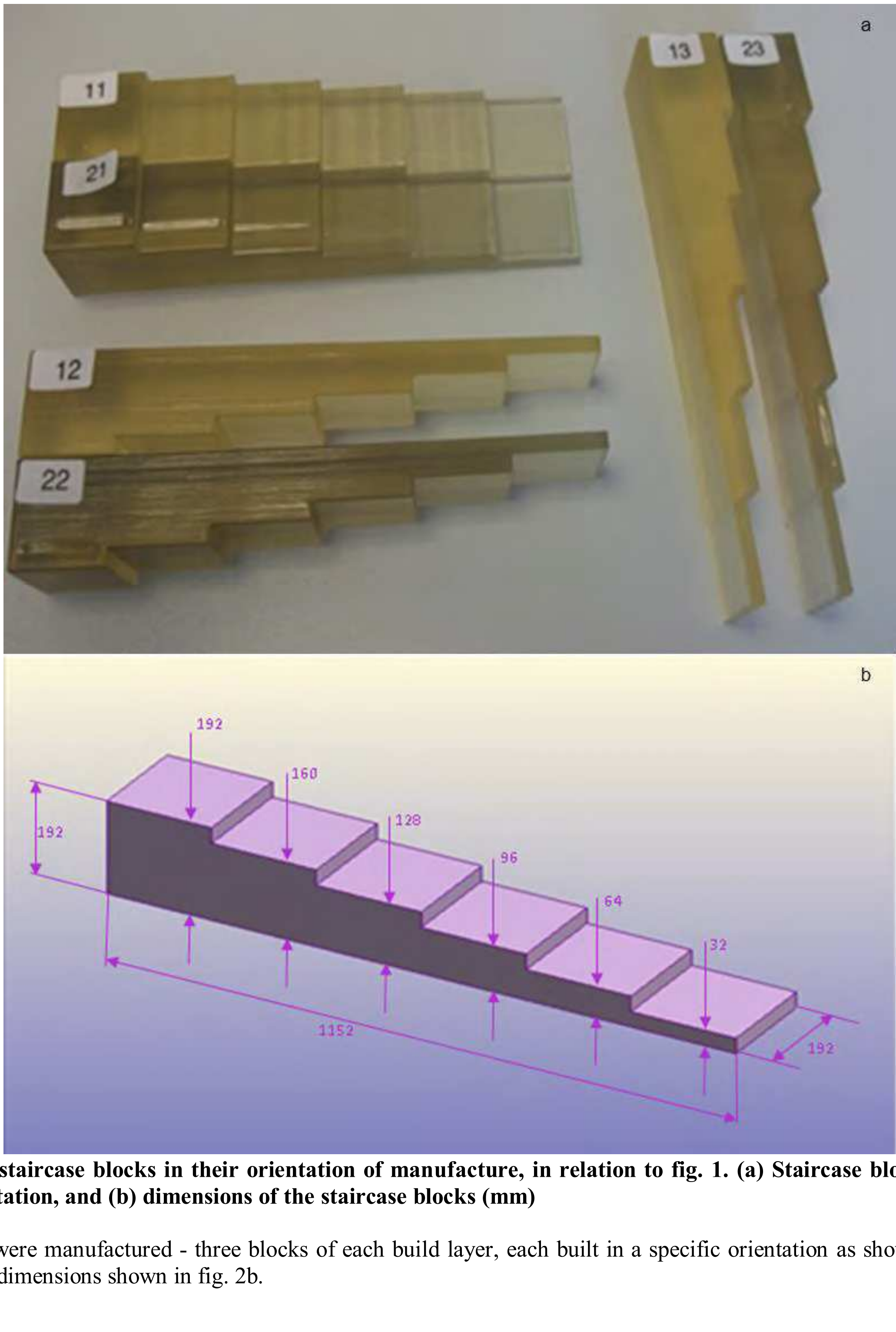

Fig. 2 The staircase blocks in their orientation of manufacture, in relation to fig. 1. (a) Staircase blocks in their build orientation, and (b) dimensions of the staircase blocks (mm)

Six blocks were manufactured - three blocks of each build layer, each built in a specific orientation as shown in figs. 1 and 2, with dimensions shown in fig. 2b.

Results

An initial visual inspection was carried out in the circular polariscope in dark field configuration, as shown in fig. 3. In order to present a clear contrast in the resulting fringe orders and allow for the same conditions throughout the analytical process, the staircase blocks were separated into their build-up layer categories, and stacked on top of each other, with the thinnest through-thickness at the farthest left in both set-ups.

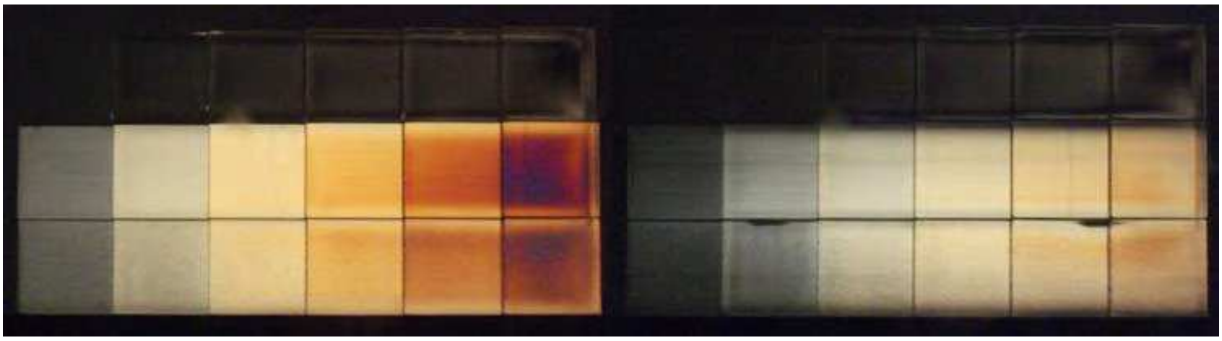

Fig. 3 Dark-field fringe information of the staircase blocks for the build-up layers, 16µm (left) and 32µm (right) The blocks are stacked on top of each other in the order block 1(top), block 2 (centre) and block 3 (bottom) and viewed in the Z direction– from the definitions in fig. 1

From visual inspection, it is seen that there is an increase in fringe order as the through-thickness of the specimen increases. This is mostly evident in blocks 2 and 3, which display significant fringe orders. Therefore an increase in transmission length gives a higher fringe order, because the light has a further travelling distance and therefore retardation - hence the difference in refraction is greater, when we consider that the difference in principle stresses remains constant (eq. 1).

It is also evident that the build orientation is highly significant if residual strains are to be alleviated. As shown in fig. 3, the blocks built in the z-direction have negligible residual strain when the through-thickness is viewed – they display dark fringes throughout all the thicknesses. This allows for the testing of a component in its green state – depending on the thickness. However, as the thickness increases, the black fringes appear to be slightly lighter, which signifies that there is some residual strain in the component at a thickness above the optimal thickness. As thickness increases, there tends to be a slight change in residual strain, although not as significant as in the other build directions. Using this method, it is more evident to discern the changes in fringe order, hence select a suitable range of thicknesses, in this case below 15mm.

It is also seen in fig. 3 that there is a similarity between the X and Y build orientations, with the variation increasing with a change in through-thickness. This could be useful when constructing components whose loading information is required in two directions. As identified in fig. 4, the residual stress from a side profile changes significantly, showing blocks 2 and 3, built in orientations x and y (fig. 1) now possess virtually no residual strains. The stacking arrangement is still the same as in figs. 2 and 3, with the exception of block 2 (central block) being inverted for balancing purposes. However, the results still harmonize with block 3.

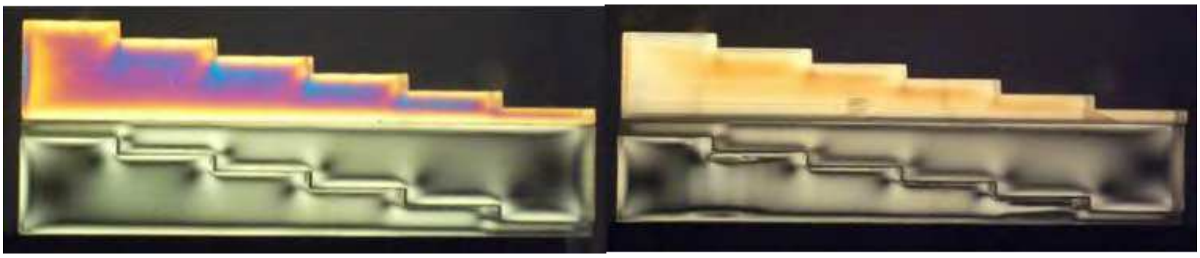

Fig. 4 Dark-field fringe information of the side profile of the staircase blocks for the build-up layers, 16µm (left) and 32µm (right) In this case, the blocks are being viewed in the X-Y plane which yields residual strain in block 1, as the staircase build layers are stacked in this plane, causing the shrinkage of the block to be most prominent

It has also been established that the finer the build-up layer, the greater the residual strains experienced in the component. Referring to figs. 3 and 4, the blocks with a build-up layer of 16 µm (left) had the greater possession of residual strains in comparison to those with the build-up layer of 32µm. To confirm this, null balance compensation was implemented to determine the specific variation (shown in fig. 5). When a smaller build-up layer is implemented (closed symbols), there are more partitions in the component that undergo curing and therefore there is greater shrinkage in the component, leading to greater residual strains.

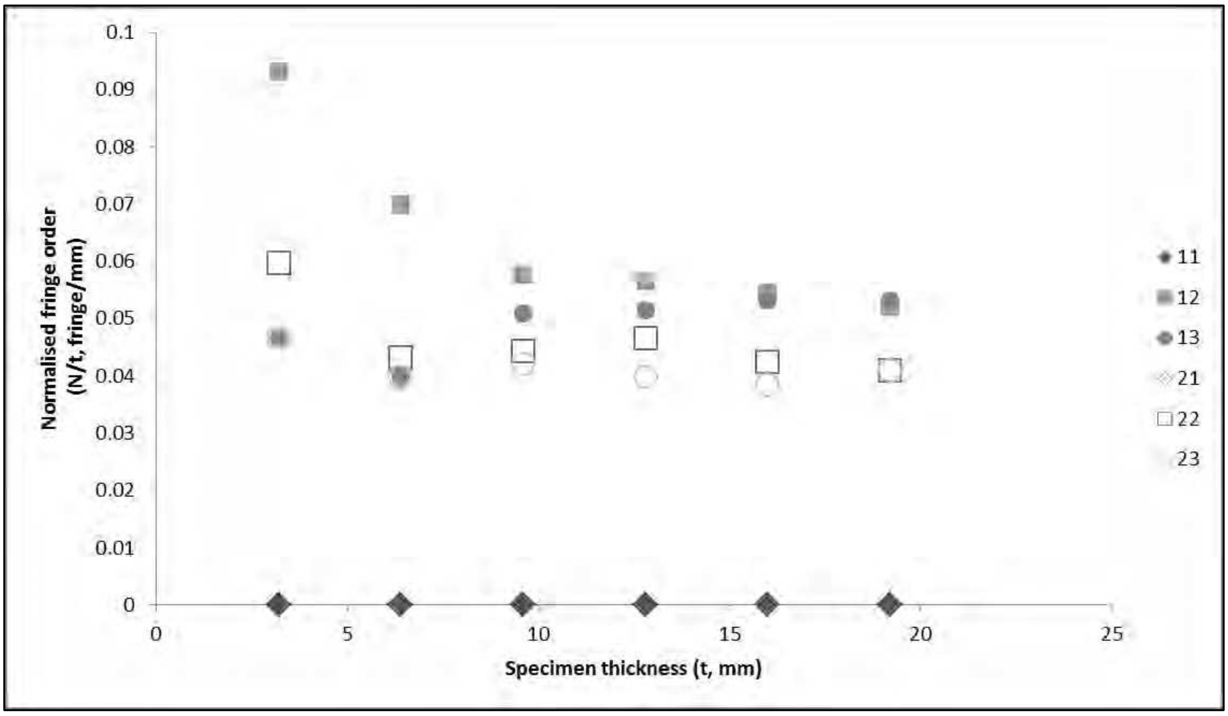

Fig. 5 Numerical results of the Null Balance Compensation for the test specimen as labelled in table (2), showing evidently that build orientation 1 is ideal as it contains minimal residual stresses when viewed in the Z direction

Because it has been established that the blocks with the 16µm build-up layer possessed greater residual strains, those with the 32µm build-up layer were analysed to complete a comparative analysis between the three named photoelastic methods that tests for their performance at low strains. The results yielded when all methods are compared numerically indicate that at very small specimen through-thicknesses, there exists a wide margin error between all three photoelastic techniques, as represented graphically in fig. 6. This resulting margin is especially true for the Tardy method, which, as indicated, has the greatest variation from all the other methods. Also, the phase-stepped values of the second 'stair', in both samples 22 and 23 have an anomalous result, which will be investigated further. If these two points are discounted, the resulting plots relating through thickness to normalised fringe order is consistent with the null balance results. The reason for this is that once the thickness has been normalised, there should be consistency in the fringe order throughout the specimen. However, at thicknesses above 10mm, the residual strain has greater consistency through all the methods, and, therefore, from this analysis, it is suggested, if utilising the Tardy method with any of the others for comparative analysis, the specimen thickness should be no less than 10mm if residual strains are to be quantified, rather than annealed whilst viewing specimen in all three dimensions.

Nevertheless, as shown in fig. 6a, the phase-stepping result indicates that if an orientation, such as that which was used to manufacture block 21, is being used to create a component and one direction of view is the sole interest, it is more advantageous to work with through-thicknesses below 15mm. From visual inspection via Tardy Method and Null Balance Compensation, the orientation yields zero residual strain. However, when phase-stepping is implemented, it is seen that residual strains are present – although the normalised fringe order is approximately 0.01 fringe/mm for a range of through-thicknesses, but it changes greatly at a thickness above 15mm. This is a possible indication that there are triaxial effects causing distortion if the component produced has a through-thickness above 15mm.

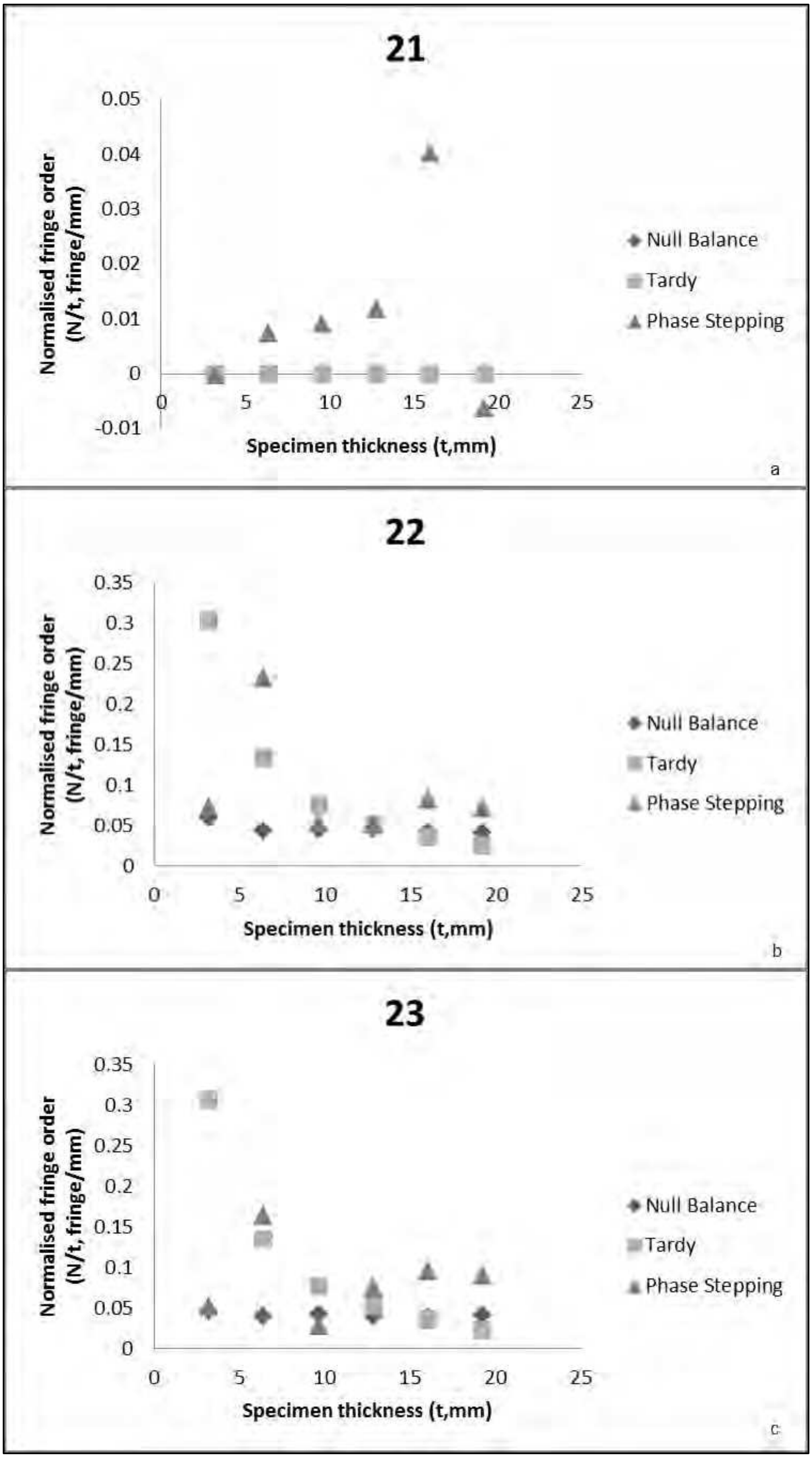

Fig. 6 Numerical results comparing the three analytical methods for the 32µm staircase blocks (a) 21, which allows the identification of low values of N, (b) 22 and (c) 23, which display similar results indicating that there are relatively uniform residual strains through the thickness, especially at through-thicknesses above 10mm when all methods are utilised

Conclusion

In this application, it has been established that it is possible to test a material in its green state after 3D printing, as, if the component is built in a specific orientation (in this case, Z direction), when analysed for residual stresses, they are negligible. This implies that loads can be applied in that direction to the material, and the residual stresses will not superpose any information onto the results. However, it was also recognised that this is true for a narrow thickness range, between 10mm and 15mm, and for a thorough analysis, it is best to apply a digital photoelasticity technique, such as phase stepping, as it allows for greater accuracy, as there is no element of human judgement in the determination of the residual strains experienced in components built via 3D printing.

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