USING DIGITAL IMAGE CORRELATION TO STUDY THE STRAIN IN HISTORIC TAPESTRIES

ALIFAH ILYANA BINTI MOHD FARIDZ

2270252M

Supervised by Philip Harrison

A project report submitted in partial

fulfilment of the requirement for the award of the

BEng Mechanical Engineering

James Watt School of Engineering

University of Glasgow

May 2020

ABSTRACT

The conservation process of historic tapestries is time-consuming, labour intensive and requires high cost. This project explores the potential of Digital Image Correlation (DIC) as a tool to measure the strain across the surface of a hanging historic tapestry. Using a Tapestry Toolkit app developed by a researcher in the University of Glasgow, the tapestry image undergoes “synthetic” deformation fields which are generated by mapping the details of a given tapestry image into finite element analyses. Deformed images are generated and then used in the DIC software to calculate its strain. To get the best result in the DIC, this project study four different variable: mesh density, image quality, subset size and the heterogeneity of the tapestry image. From the results, it could be seen that smaller mesh density and larger subset size produce better results, the brightness of the tapestry image greatly influence the strain distribution and heterogenous tapestry image results in higher strain than homogenous tapestry image.

ACKNOWLEDGEMENT

I would like to thank my supervisor, Philip Harrison for the support and guidance on the project. Kenneth Nwanoro for his Tapestry Toolkit and his assistance in helping me understand how to use the toolkit, GOM and Ncorr. Rosa Constantini for teaching me about VIC-2D and show me the project that she has been working on. I would also like to thank Zhaofei Xiao and John Davidson for helping me with the lab procedure in the early stage before this project changed its direction.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

1 INTRODUCTION

1.1 Background of Study

Tapestries have been introduced to the world since the 14^{th} century. Back then tapestries have multiple purposes such as decoration and as a method to display a depiction of religious scenes. Today, historic tapestries are precious because they can be considered as a nation's heritage. Conservation of tapestry is not an easy job because the size of historic tapestries can be as large as 10m x 10m and can be as heavy as 100kg. Conservators and curators are constantly looking for the best way to conserve historic tapestries and one of the methods is using Digital Image Correlation (DIC). By using DIC to study the strain across the tapestries, the deterioration of a tapestry could be predicted. The results from the test could then be related to the deformation of the actual material to predict its likely future behaviour. Appropriate changes could then be made to its display conditions and hence the failure of the tapestry could be avoided or delayed.

1.2 Problem Statement

Since historic tapestries are made from natural fibres, they are susceptible to changes in their chemical nature, caused by environmental variables such as humidity, exposure to lights and temperature. Another reason which causes their physical damage is their self-weight. Historic tapestries are typically a few meters wide by a few meters long, so they are relatively heavy. The damages caused by the self-loading is accentuated especially at its weakest point (e.g. slits, tears, and holes).

The current conservation process for historic tapestries are labour intensive, time-consuming and it requires high cost. Since historic tapestries are considered a nation's heritage, the conservators and curators need to find the best way to conserve and display them. To do that, there is a need to study the strain distribution acting across the tapestries [1].

1.3 Objective of the Study

This project aims to study the validity of DIC as a mode of monitoring the strains in historic tapestries without the use of speckle pattern. Since this method would solely depend on the heterogeneity of the tapestry image to detect the displacement, it is prone to errors. In this study, the degrees of error will be investigated and compared with numerical analysis so that the accuracy of experimental results can be validated.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Tapestries

The world knows about tapestries in diverse cultures from hundreds of years ago. In the past, tapestries are only common amongst the aristocrats since it is expensive; tapestries can symbolise power and wealth. In 1540s, Henry VIII commissioned a large number of tapestries to accentuate his new power and position as the head of the Church of England [2]. Tapestries are usually commissioned to depict a religious scene or to commemorate historic events. They also have a practical function which is to provide insulation to the cold walls and sometimes to provide comfort and decoration when the royals and nobles went travelling [3].

Tapestries are made by having the coloured weft thread cover the plain warp thread. Usually, the weft part is done one by one, according to the colour for the design in question. This technique causes some slits in the weave structure which creates weak joins as can be seen in Figure 1.

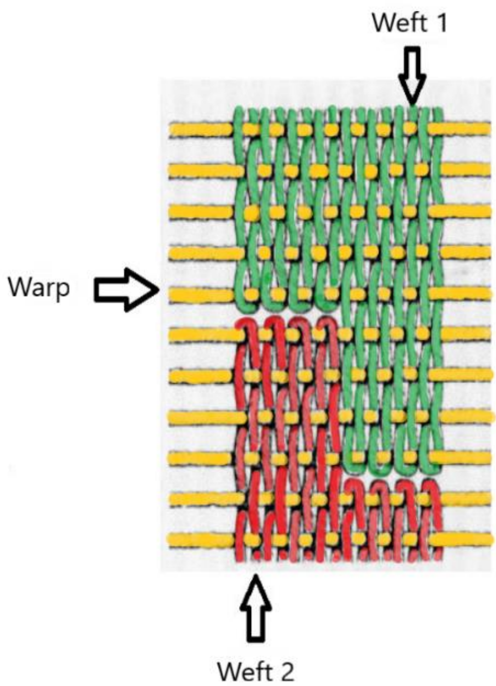


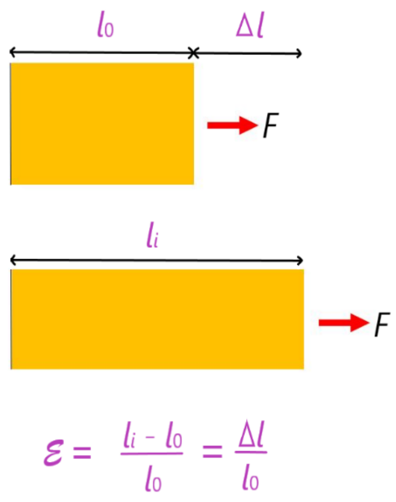
Figure 1 Showing the schematic of the slits occurring between different coloured weft regions of the tapestry

2.1.1 Conservation of historic tapestries

Source: Tapestry Conservation: Principles and Practice

Figure 2 (a) a team of conservators attaching Velcro to tapestry as part of conservative process, (b) and (c) conservators working to take down the tapestry from the wall, (d) the tapestry being transported to the conservation site in a large packing case [4]

2.2 Strain



Engineering strain E is extension per unit length in which l_o is the original length before any load is applied and l_i is the instantaneous length, l_o - l_i is the change in length at some instant as referenced to the original length. Strain is unitless.

Figure 3 Showing that strain is the relative amount of displacement and it has no unit

2.3 DIC

Digital Image Correlation is a non-contact full-field experimental strain measurement technique. It has been used successfully for the examination of strains in tapestries [5]. DIC works by tracking the 3D surface displacement of a deformed object using grey-scale image patterns. The displacement vector field is then used to obtain strain distributions [6]. DIC is usually used with a speckle pattern, which is obtained by printing or spraying paints on the surface of the specimen to ensure a more accurate full-field displacement data. This is not applicable when it comes to historic tapestries. However, since most tapestries have a heterogeneous surface due to its complex and intricate image, it becomes a favourable property to be used with DIC.

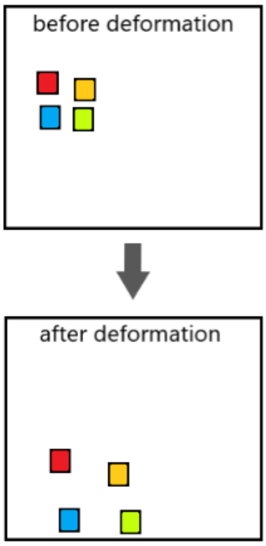


Figure 4 The location of four different pixels before and after deformation. DIC software calculates the difference between location of pixels of the different images and correlates them to determine the deformation.

2.4 Previous Research

According to [6], after long exposure to a certain humidity and temperature, the tapestry may experience creep because the size of a historic tapestry tends to be relatively large and heavyweight. This study found out that the strain increases with the increase in humidity.

From [5], this study tries to use 3D digital image correlation to track displacements and strains of canvas paintings exposed to relative humidity changes and it manages to find the relation between those two.

A study of [3] found out that from the FEA performed to model a hanging tapestry, the slits in the structure results in point of high-stress concentration and distortion in stress distribution occur at the area where two different materials met.

A study from [7] said that the size of a subset should be large enough to achieve a reliable correlation analysis in DIC, this is because a large subset size can ensure there is sufficiently distinctive intensity pattern contained in the subset to differentiate itself from the other subsets. Although it may seem that large subset is desirable, it may lead to errors in the approximation of the underlying deformations.

A result from the study [1] found that smaller subset size provides greater resolution, but it increases the error for the tracking images of speckles and the tapestry.

CHAPTER 3

3 METHODS

This project used a combination of finite element analysis and DIC. An application called Tapestry Toolkit is used to perform synthetic deformation on a tapestry image to imitate a real historic tapestry under stretching condition. Then, different DIC software is used to analyse the deformed images of the tapestry and to get the full-field strain map across the tapestry image.

3.1 Tapestry Toolkit

Tapestry toolkit is an application developed by Kenneth Nwanoro, a researcher at the University of Glasgow. This app is designed using MATLAB code with the main purpose of visualising and quantifying the error that will be associated with the tapestry image analysis. This app will allow conservators to run a non-contact, non-destructive test on any tapestry with inherent images to study the strain distribution across its surface.

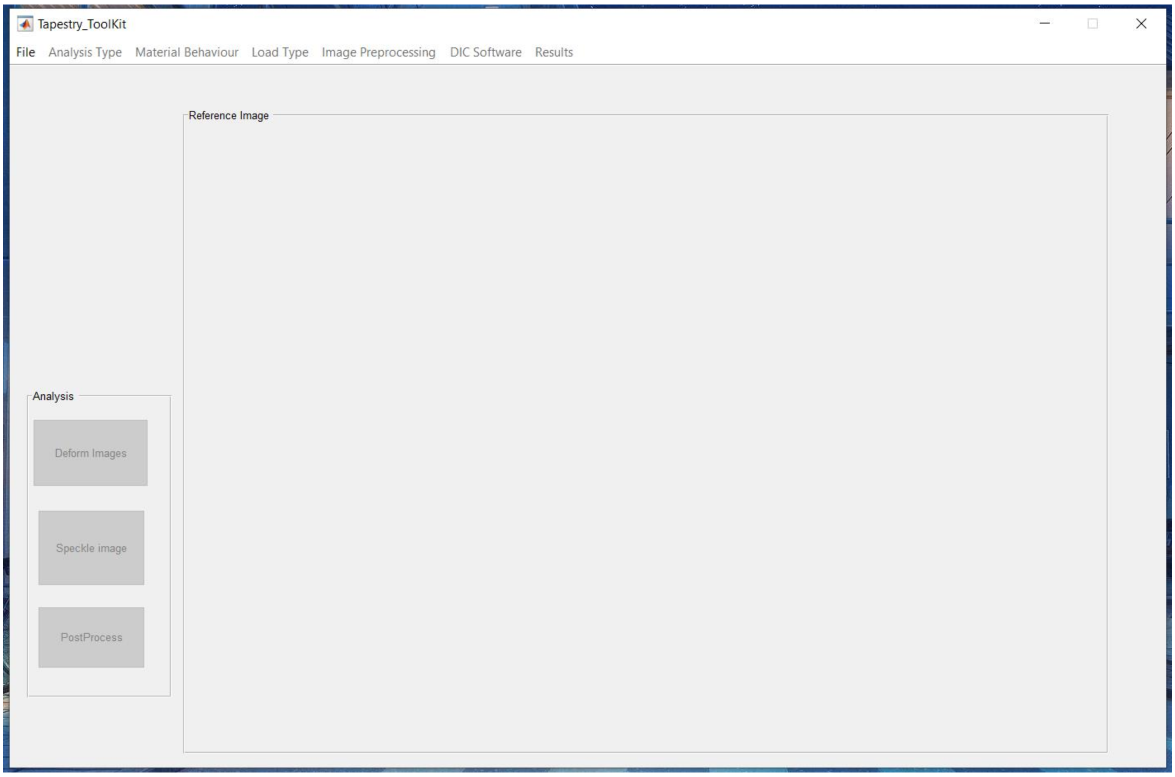


Figure 5 User interface of the Tapestry Toolkit

3.1.1 Steps to use the Tapestry Toolkit

Firstly, a chosen image of tapestry is submitted into the toolkit. In this project, the tapestry image chosen is shown in Figure *6* because of its complex and intricate feature, this is to ensure the displacement can be captured in DIC software. Then the analysis type is chosen, static type is used. Linear static is chosen for its material behaviour then the material properties such as Young's Modulus and Poison's ratio is inserted. The mesh density is one of the variables that is studied in this project so different sizes of mesh density are used. As for the Region of Interest, the whole image is used to get the full-field strain map. After all appropriate steps have been set, the image will be deformed to get 5 deformed images. In this project, only the in-built FEA is used because it is difficult to get the ABAQUS software on the same PC/laptop which has the Tapestry Toolkit. Due to this constraint, the lowest mesh density that can be used is 10. Smaller mesh density needs to use a supercomputer since it takes more computational time. The deformed images of the tapestry are compared with the deformed images of the speckle image. Both are then analysed in DIC software. The post-processed data are used in the toolkit again to get the strain distribution map and the error map. The results between the tapestry image and the speckle image are compared to study the viability of DIC in measuring the strain distribution across the tapestry image which is 'synthetically' deformed.

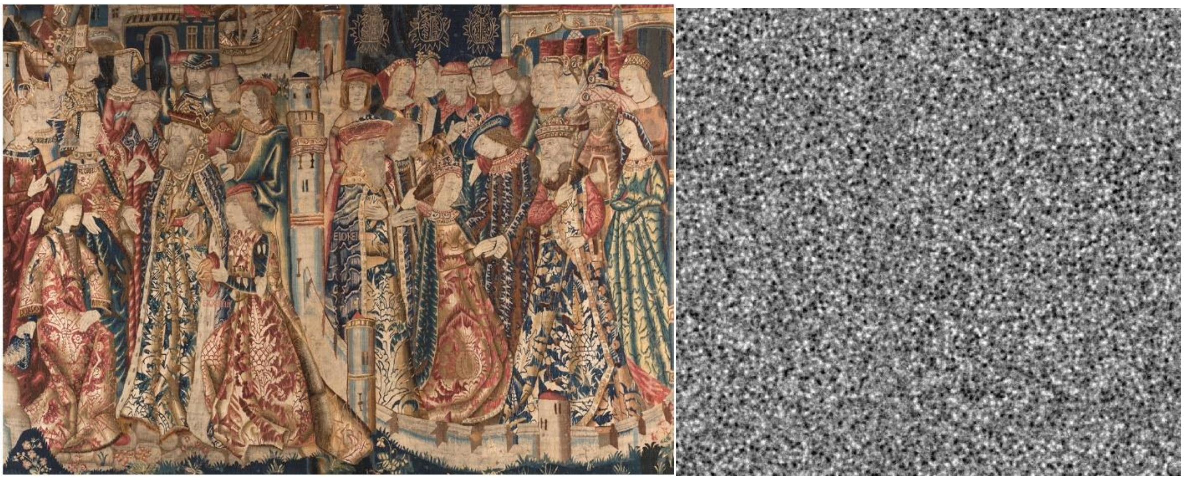


Figure 6 Tapestry image and Speckle image use in this study

3.2 DIC Software

In this project, three different DIC software is used. The main idea is to compare the ease of use of the DIC software. The reason why this project needs to take note on the usability of each tool is that in the future, the target user (conservators and curators) might have zero knowledge on this topic. Therefore, the findings might help them.

3.2.1 VIC-2D

This software allows the measurement of full-field, in-plane displacements.

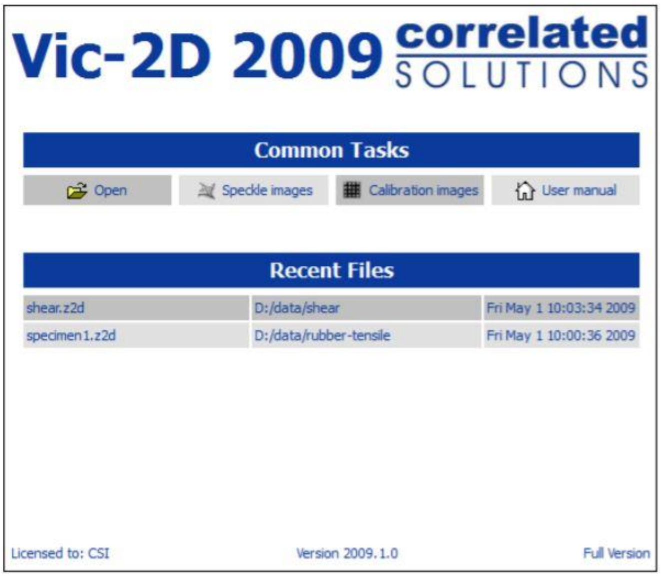


Figure 7 VIC-2D start-up interface

3.2.2 NCORR

This software is an open-source 2D digital image correlation MATLAB program. It is wholly contained within the MATLAB environment; it has plotting tools to create figures.

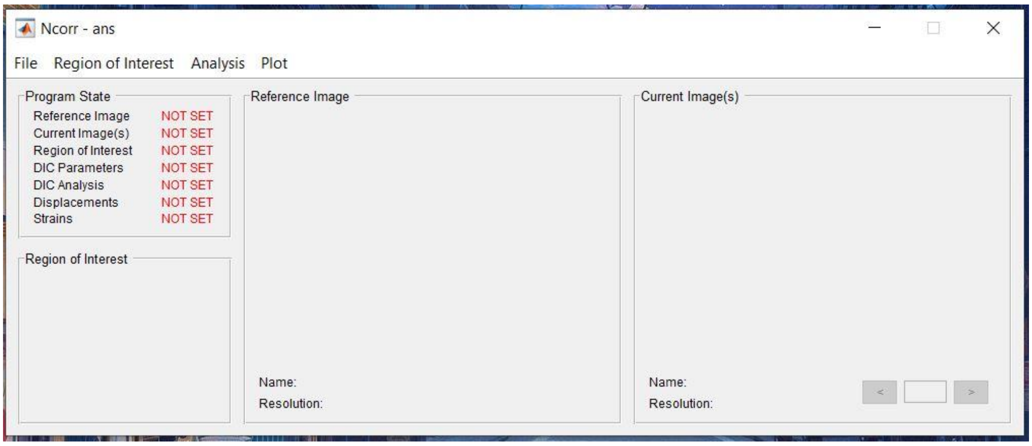


Figure 8 NCORR user interface

3.2.3 GOM Correlate

This software offers a free version that can be downloaded from their website.

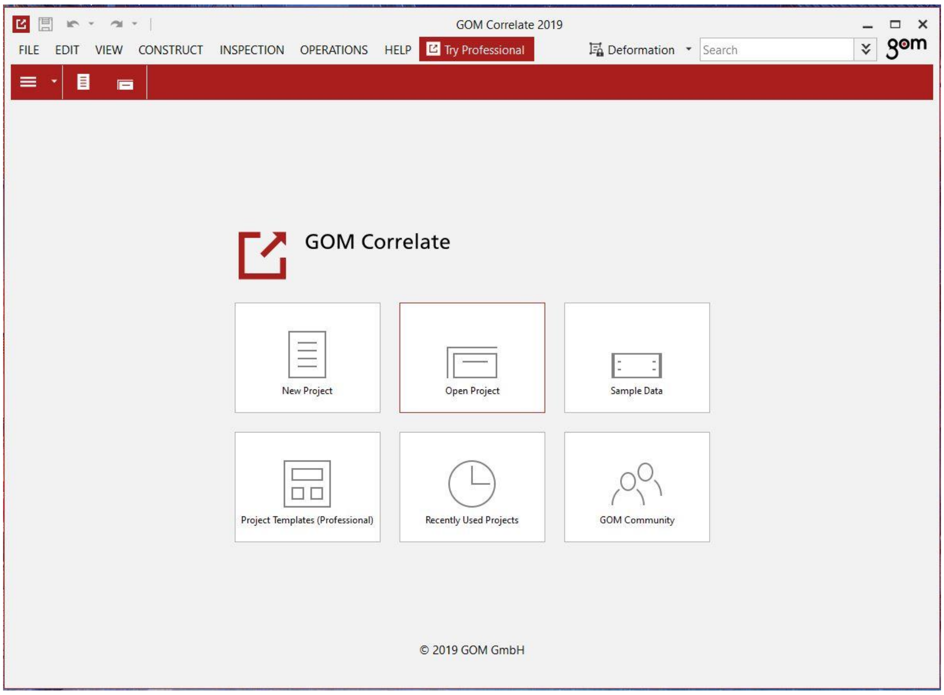


Figure 9 GOM user interface

3.3 Reliability of the DIC

To study the reliability of DIC in historic tapestries conservation, there are a few parameters that need to be considered so that the error can be minimised and to obtain more accurate and reliable results.

3.3.1 Mesh density

Mesh density is the number of elements per unit area in a mesh. Higher density meshes usually produce more accurate results, but it takes longer to analyse. In this project, the mesh density compared is 40 and 10.

Figure 10 FEA mesh view for mesh density 40

Figure 11 FEA mesh view for mesh density 10

3.3.2 Image quality

To illustrate the method and demonstrate the image-dependent effectiveness of DIC in analysing historic tapestries, the brightness of the image is changed, and the error is compared.

Figure 12 Tapestry image for brightness test

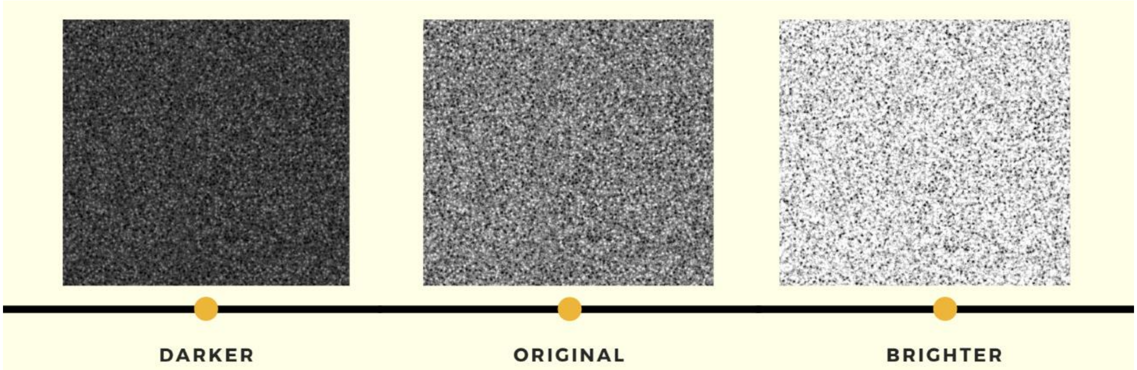


Figure 13 Speckle image for brightness test

3.3.3 Subset size

To achieve a reliable correlation analysis in DIC, the size of a subset should be large enough so that there is a sufficiently distinctive intensity pattern contained in the subset to distinguish itself from other subsets. In this project, the subset size compared is 21, 42 and 84.

3.3.4 Heterogeneity of the tapestry

To evaluate the potential of image-based DIC in measuring full-field strains, a more complex and intricate image of the tapestry are used. In this project, the number of materials is compared between 1 and 2. Tears and slits cannot be introduced in this project because they cannot use the in-built FEA.

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Observation on DIC software

In this topic, the observation on each DIC software is discussed from a first-time user perspective.

4.1.1 Ncorr

Ncorr is relatively easy to use for a first-time user. The user interface is simple and easy to navigate around. The fact that the function button is in ‘word’ form (e.g. Load reference image, Region of interest, etc) instead of just symbols makes it user friendly and the tutorial is easier to follow. The Program State status in *Figure 14* is really helpful because the user can see their progress and what are the next steps that they need to take. The prompt windows in Figure *15* for every new action is helpful although it feels like a bit messy sometimes. It helps the user know that they need to finish that certain task first before moving on to the next step. As can be seen in Figure *16*, the button functions are aligned properly and the way how it lights up when the function is available to be modified is helpful for the user. As for the plot function in Figure *17*, since all the plots can be generated at the same time, it helps in saving time. The image of the plot also can be saved together with the info as shown in Figure *18*, so it is easy for the user to refer to the image to compare the specifications of their analysis. The only setback is that to use Ncorr, the user need to have access to MATLAB, so this might cause a problem to the user who did not have the license.

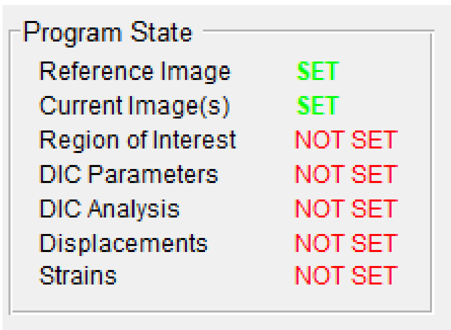
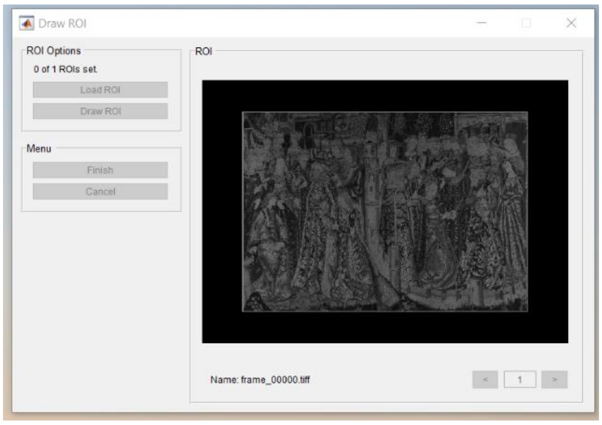
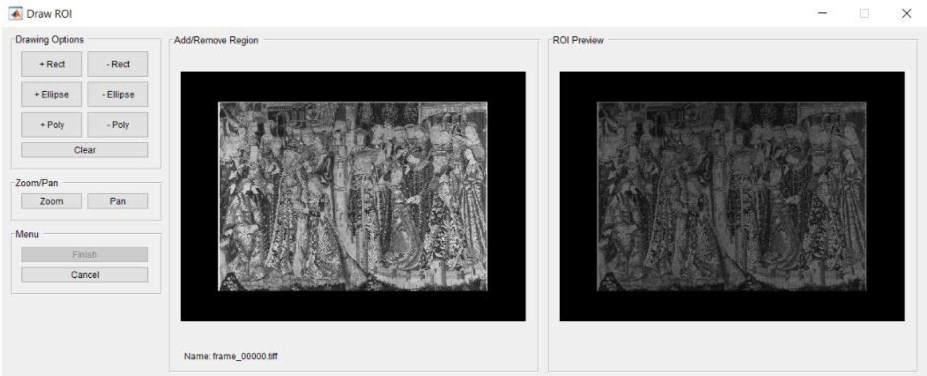


Figure 14 Program Showing user's progress



(a)



(b)

Figure 15(a) and 15(b) Pop-up prompt windows showing up for every step

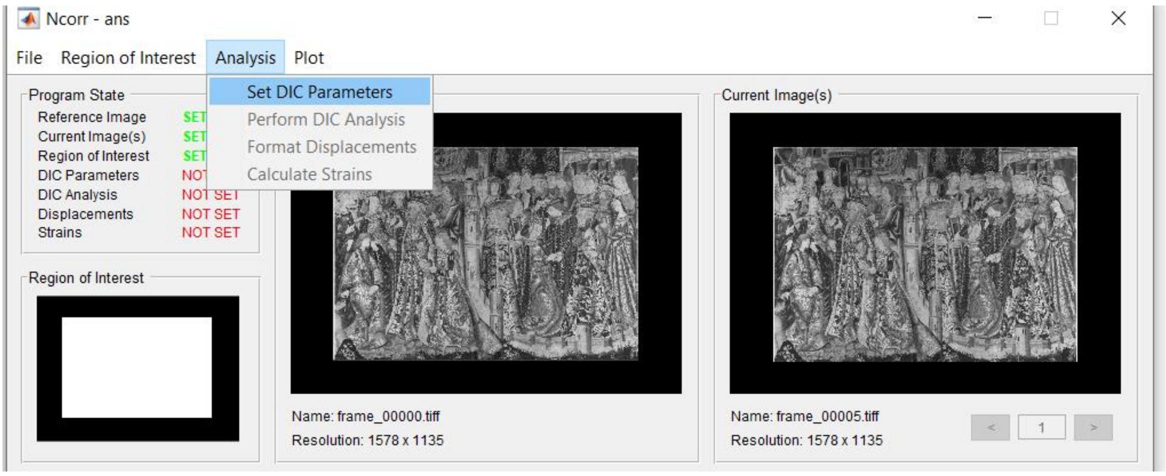


Figure 16 Function button aligned in order and lights up when available to be modified

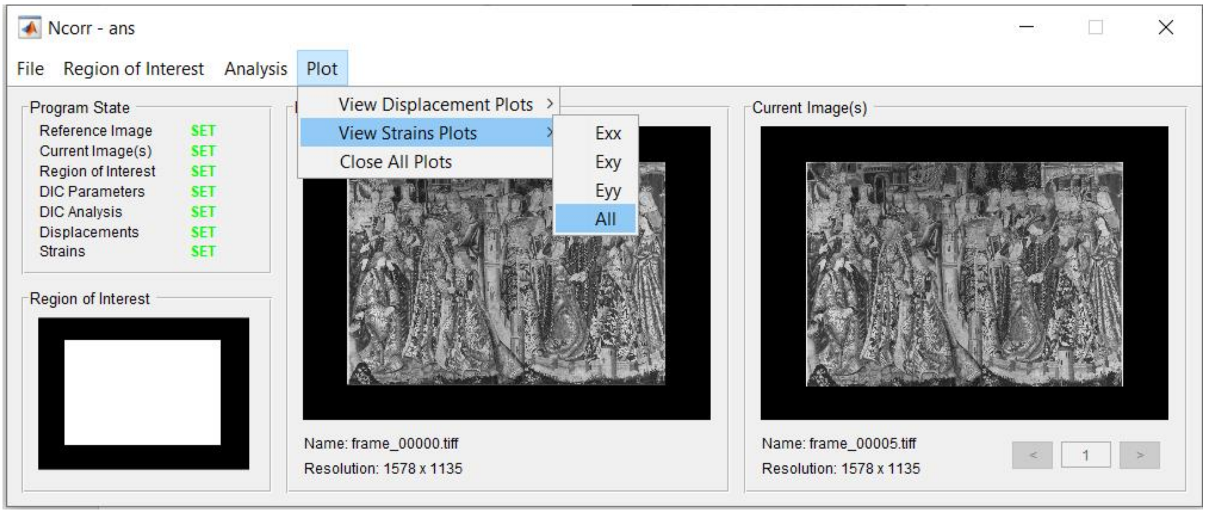


Figure 17 All plots can be generated at the same time

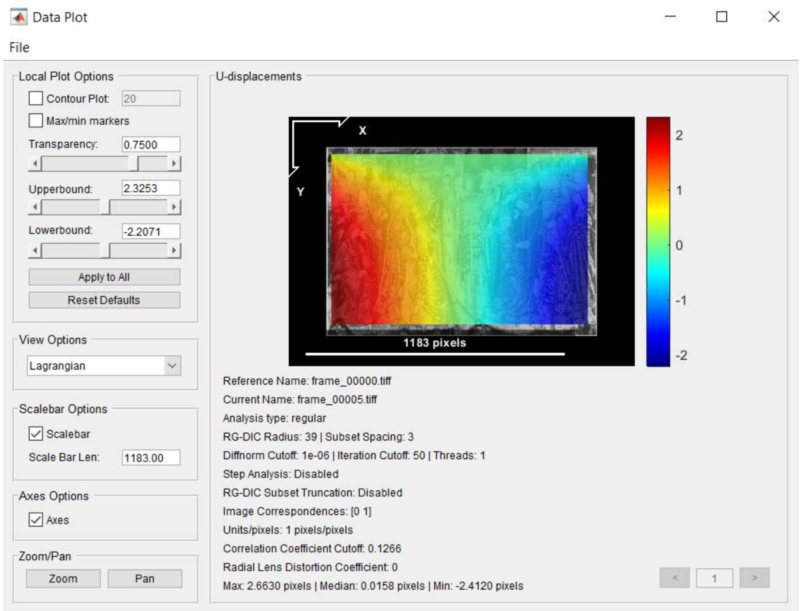


Figure 18 Image of the plot can be saved with its info

4.1.2 GOM Correlate

GOM Correlate is quite difficult to use for a first-time user. Most of the function button in the user interface is made up of 'symbols' as in Figure *19*, this makes the tutorial harder to follow because the user has to spend more time to find the correct symbol as mentioned in the tutorial. The function button lights up in order as in Figure *20*, this is a useful feature. As for the selection of Region of Interest, it is a complicated and not straight forward since the options available are drawing ROI by using polygon or circle shape only as shown in Figure *21*, so it requires more time. The plotting function only allows the graph to be generated one by one (Figure *22*), so it is time-consuming. For a first-time user, I think this software requires more time for the user to get used to. This software cannot be used for the post-processing in the Tapestry Toolkit since it cannot produce data in the MATLAB file.

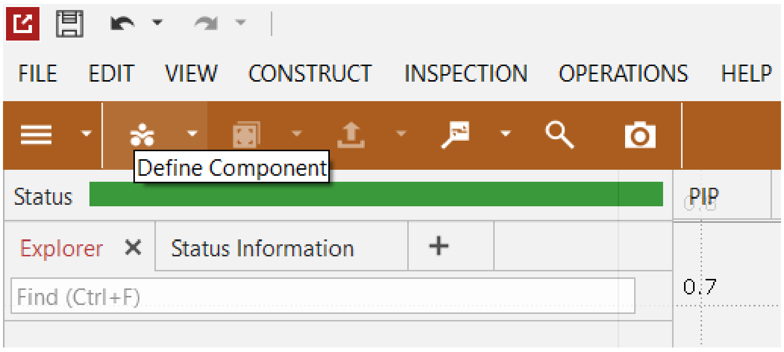


Figure 19 Function buttons shown in symbols

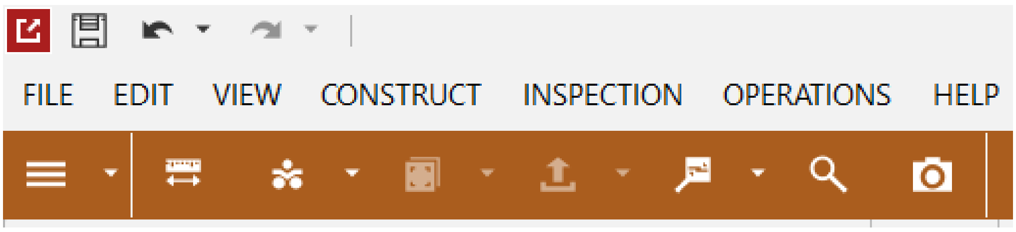


Figure 20 Function buttons light up in orders

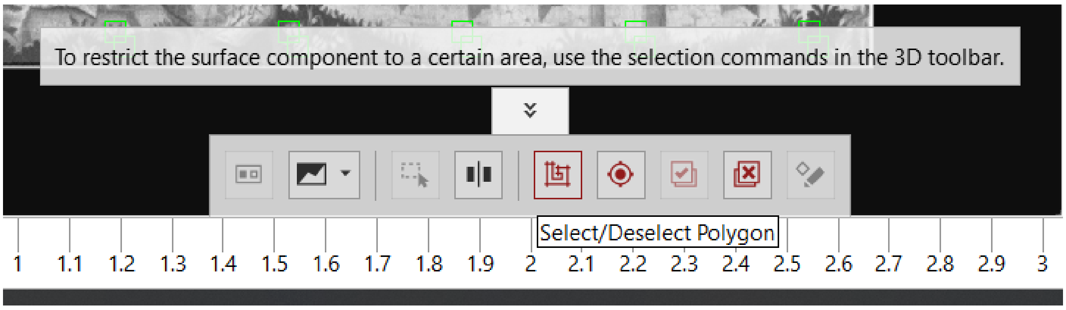


Figure 21 Function button to draw ROI

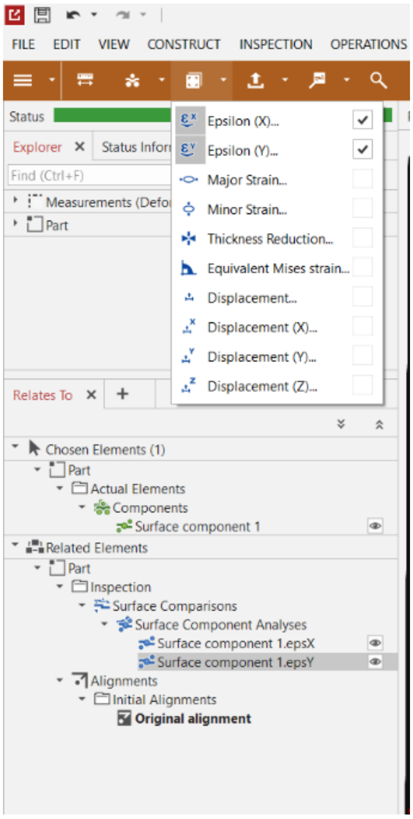


Figure 22 Options for plots

4.1.3 VIC-2D

VIC-2D or Visual Image Correlation in two-dimensional is the most user friendly. It has a simple user interface as can be seen in Figure *23* and Figure *24*. The tutorial is easy to follow, and the post-processing results are easy to understand. The post-processing data are the most compatible with the Tapestry Toolkit. The only downside is that this software is hard to get access and, in this project, since the software is on another PC, there is a lot of file transferring process occurring therefore to avoid confusion, file naming is really important.

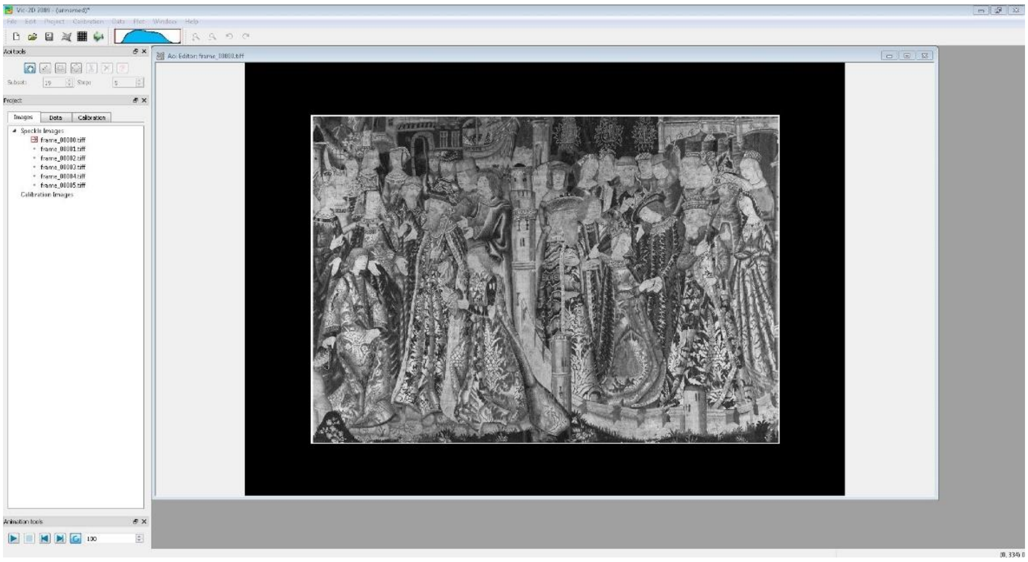


Figure 23 User interface for VIC 2D

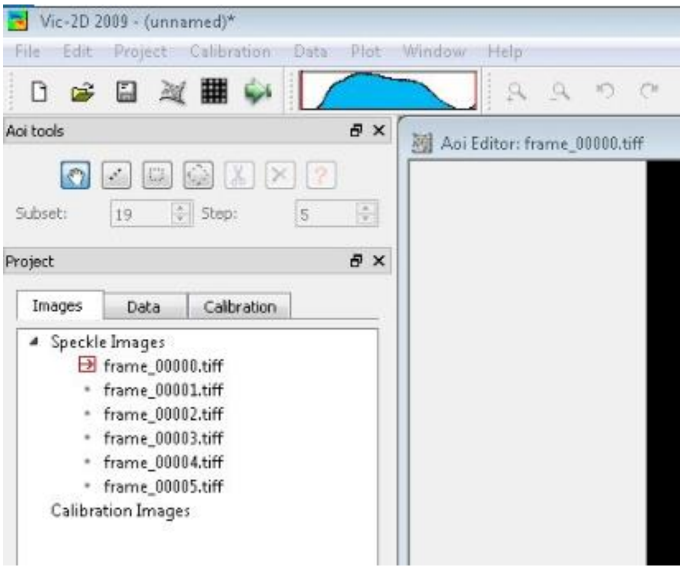


Figure 24 Easy to follow function button

4.2 Reliability test of DIC

In this part, four variables are used to find out the best condition to use with the DIC.

4.2.1 Mesh density

The mesh density size compared in this topic is 40 and 10.

Analysis type	Static	Static
Number of materials	1	1
Material behaviour	Linear static	Linear static
Young's Modulus	120	120
Poisson ratio	0.4	0.4
Load type	Displacement (stretching)	Displacement (stretching)
Time dependent	No	No
Stretch percent	1	1
Mesh density	40	10
Image scale	1	1
ROI	Whole image	Whole image
DIC software	VIC 2D	VIC 2D
FEA	In-built FEA	In-built FEA
Deformed image	5	5
Compare with speckle	Yes	Yes
Subset size	21	21

Table 1 The setting used for Mesh Density test

For this test, it is clear that smaller mesh density takes longer computational time. As for the mesh density of 40, it only takes 2 minutes for the deformation in the Tapestry Toolkit to complete meanwhile the mesh density of 10 takes 20 minutes.

From *Figure 25* and *Figure 27*, it can be seen that the strain reduces for mesh density 10. The result is more accurate because there is a greater number of elements. The difference in strain between the value predicted in FEA and the value calculated in the DIC also is smaller for the tapestry image which uses the mesh density of 10 as can be compared between *Figure 26 (b)* and *Figure 28 (b)*.

4.2.1.1 Mesh density 40

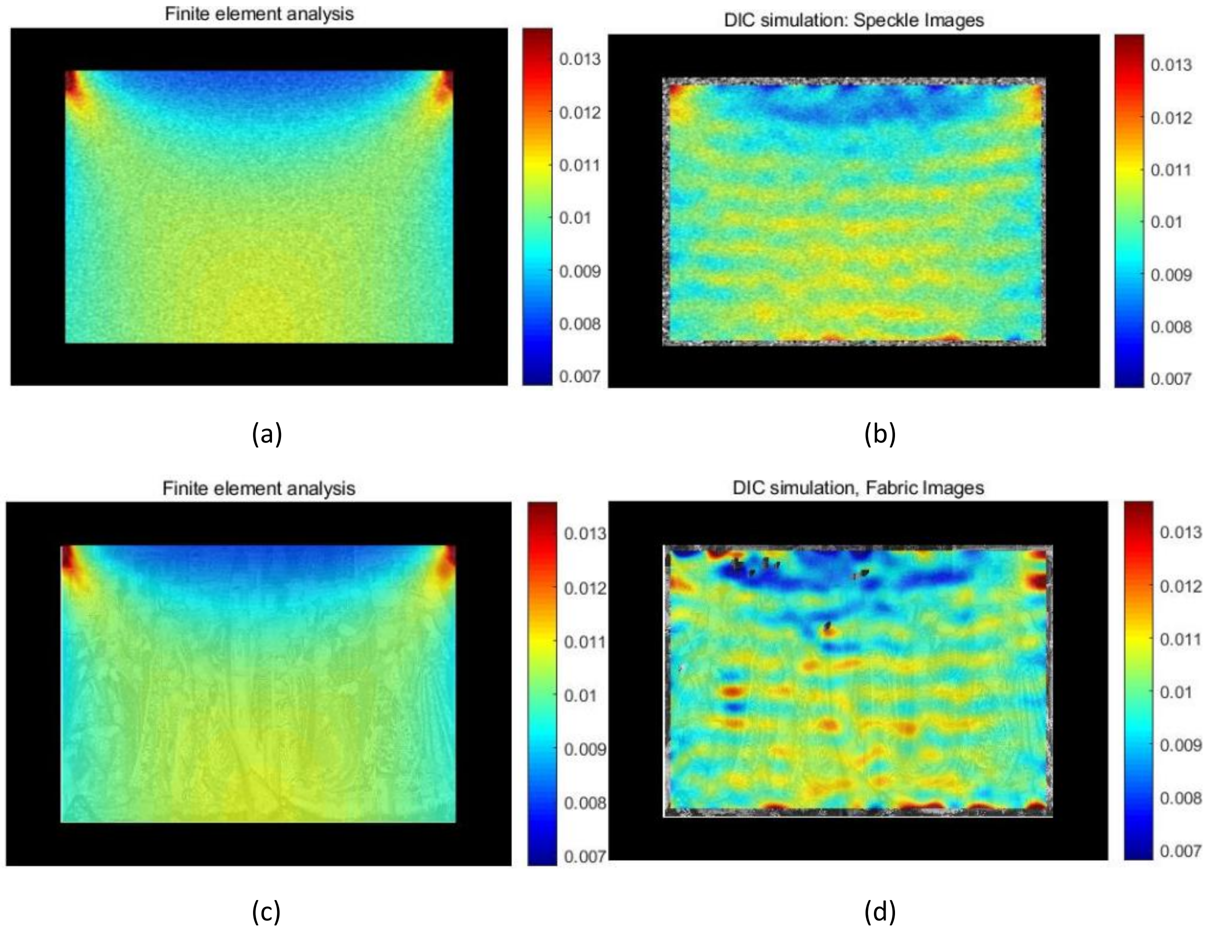


Figure 25 (a) and (c) is the strain predicted from the FEA for the speckle image and the tapestry image while (b) is the strain from calculated from the DIC for the speckle image and (d) is for the tapestry image

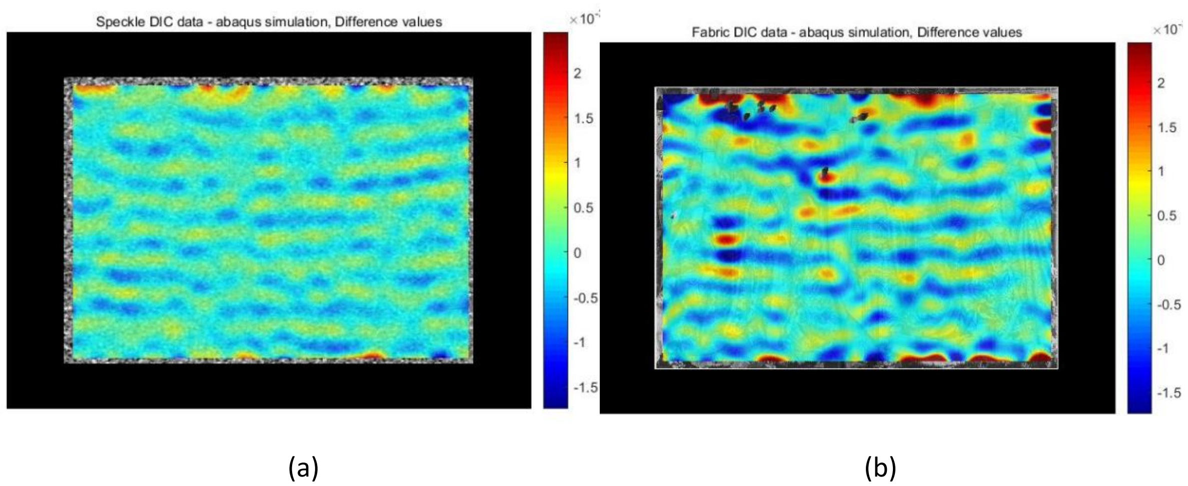


Figure 26 Difference value between FEA and DIC (a) is the difference value for the speckle image and (b) is the difference value for the tapestry image

4.2.1.2 Mesh density 10

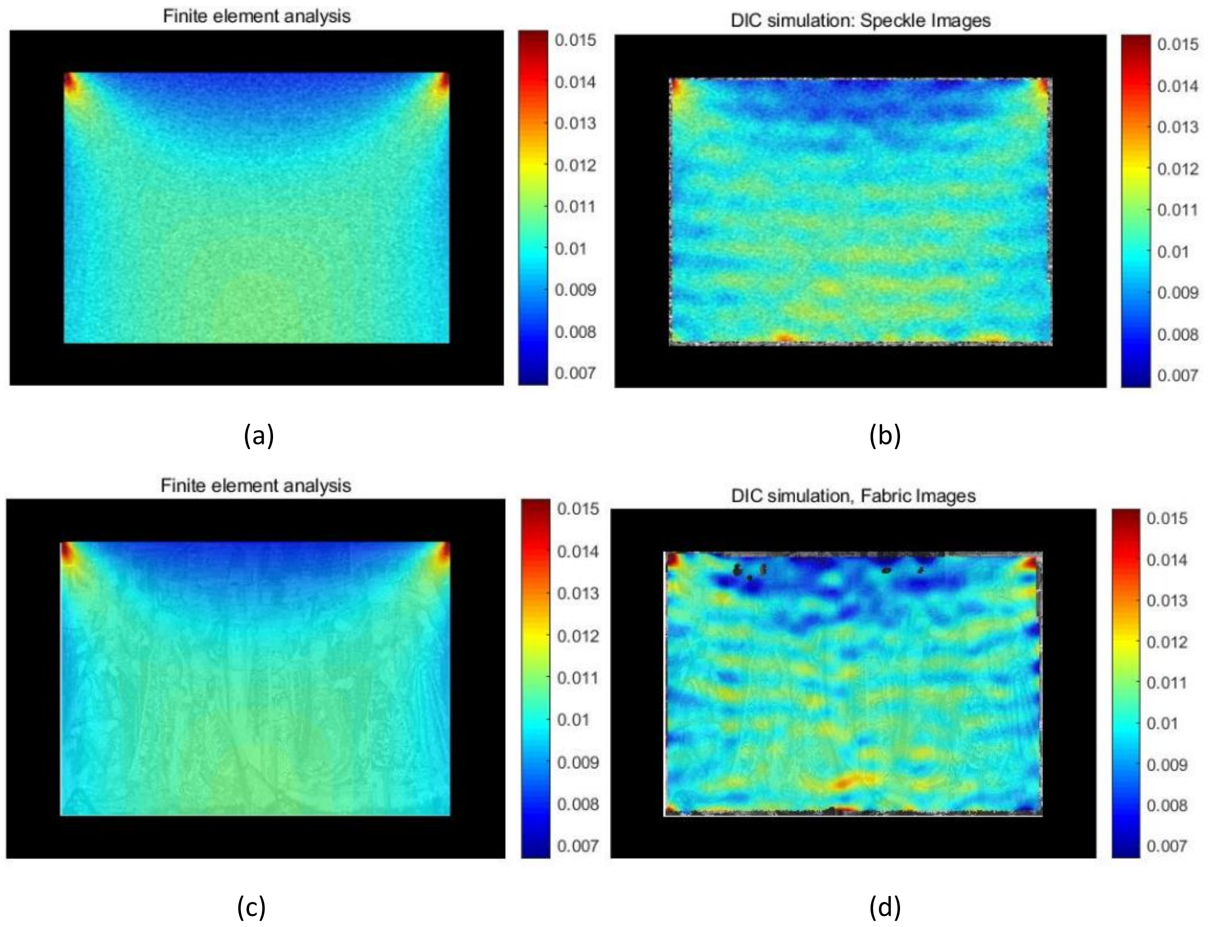


Figure 27 (a) and (c) is the strain value predicted from FEA simulation, (b) is the strain from the DIC calculation for the speckle image, (d) is the strain from the DIC for the tapestry image

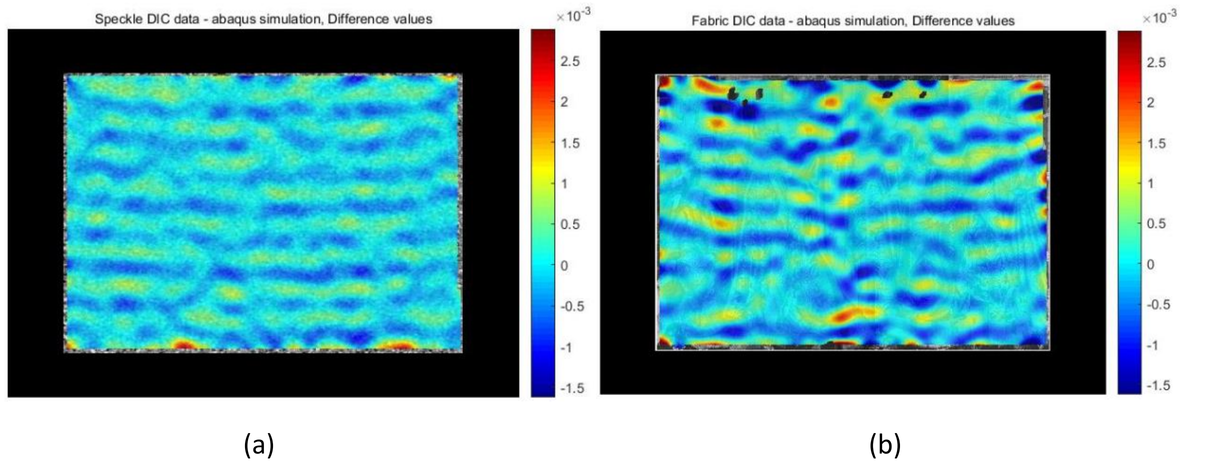


Figure 28 Difference in strain between FEA and DIC, (a) is the difference for speckle image, (b) is the difference for the tapestry image

4.2.2 Image quality (brightness)

The brightness is changed to 40% brighter and 40% darker. This is just an assumption that the place where the tapestry image is being taken might be darker or too bright.

Image type	Reference	40% Brighter	40% Darker
Analysis type	Static	Static	Static
Number of materials	1	1	1
Material behaviour	Linear static	Linear static	Linear static
Young's Modulus	120	120	120
Poisson ratio	0.4	0.4	0.4
Load type	stretching	stretching	stretching
Time dependent	No	No	No
Stretch percent	1	1	1
Mesh density	10	10	10
Image scale	1	1	1
ROI	Whole image	Whole image	Whole image
DIC software	VIC 2D	VIC 2D	VIC 2D
FEA	In-built FEA	In-built FEA	In-built FEA
Deformed image	5	5	5
Compare with speckle	Yes	Yes	Yes
Subset size	21	21	21

Table 2 The setting used for the Image Quality test

4.2.2.1 Reference Test (original)

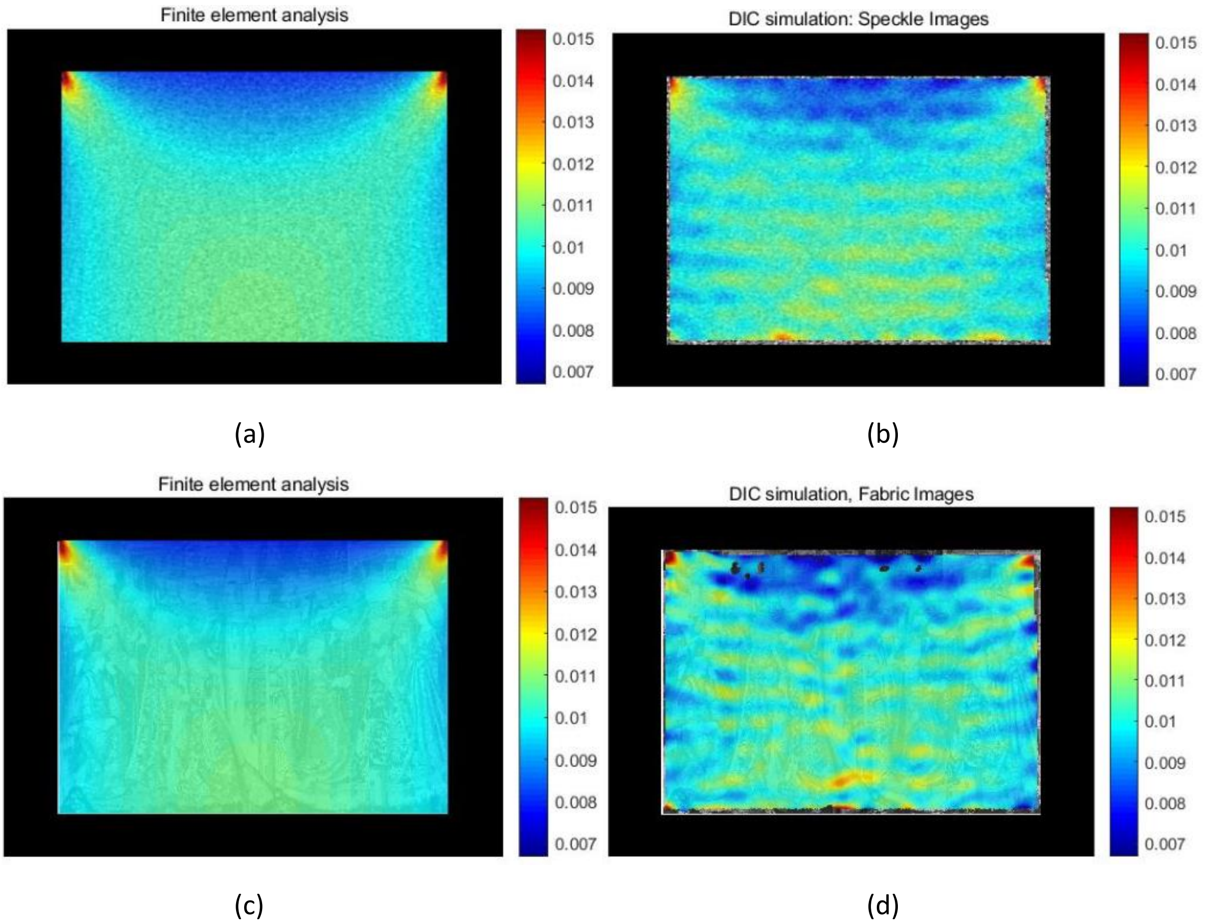


Figure 29 (a) is the stain in the reference speckle image from FEA, (b) is the strain in the reference speckle image from DIC, (c) is the strain in reference tapestry image from FEA, (d) is the strain in reference tapestry image from DIC

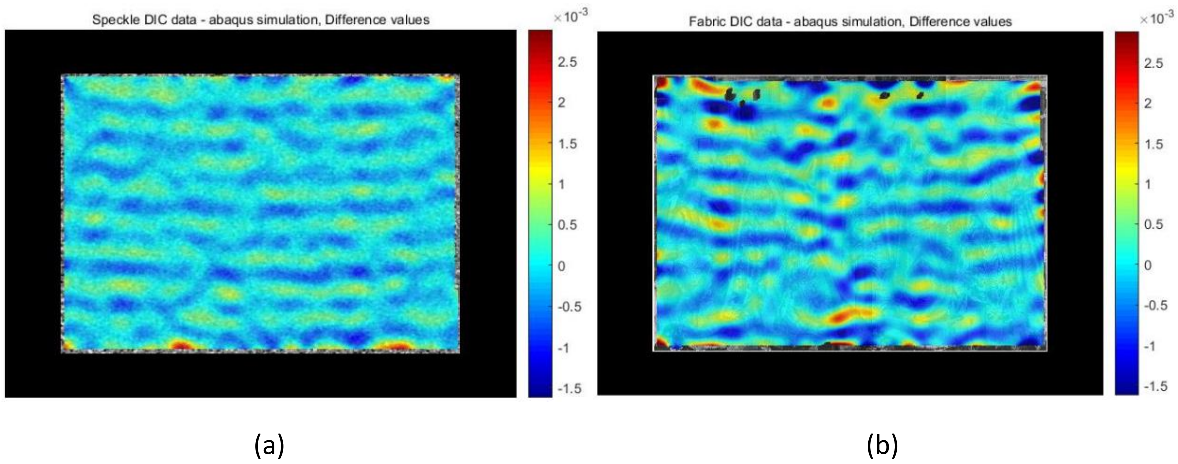
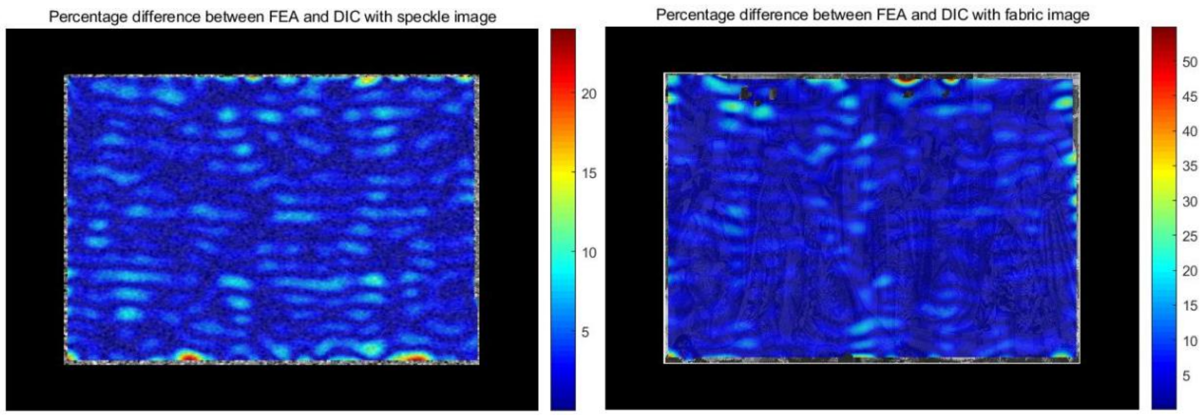


Figure 30 (a) is the difference in strain between the DIC data and the FEA data for the speckle image and (b) is the difference in strain between DIC data and FEA data for the tapestry image



(a) (b)

Figure 31 Percent error between the FEA and DIC strain, (a) is for the speckle image, (b) is for tapestry image

The strain for the tapestry image and the speckle image from the DIC show similar distribution as predicted in the FEA simulation. From the DIC calculation, the tapestry's strain and the speckle's strain is very similar although in Figure 30 the difference in tapestry strain did register some high differences, the percentage difference in Figure 31 prove that the error is small and the accuracy is similar to the speckle image.

4.2.2.2 Brighter Test

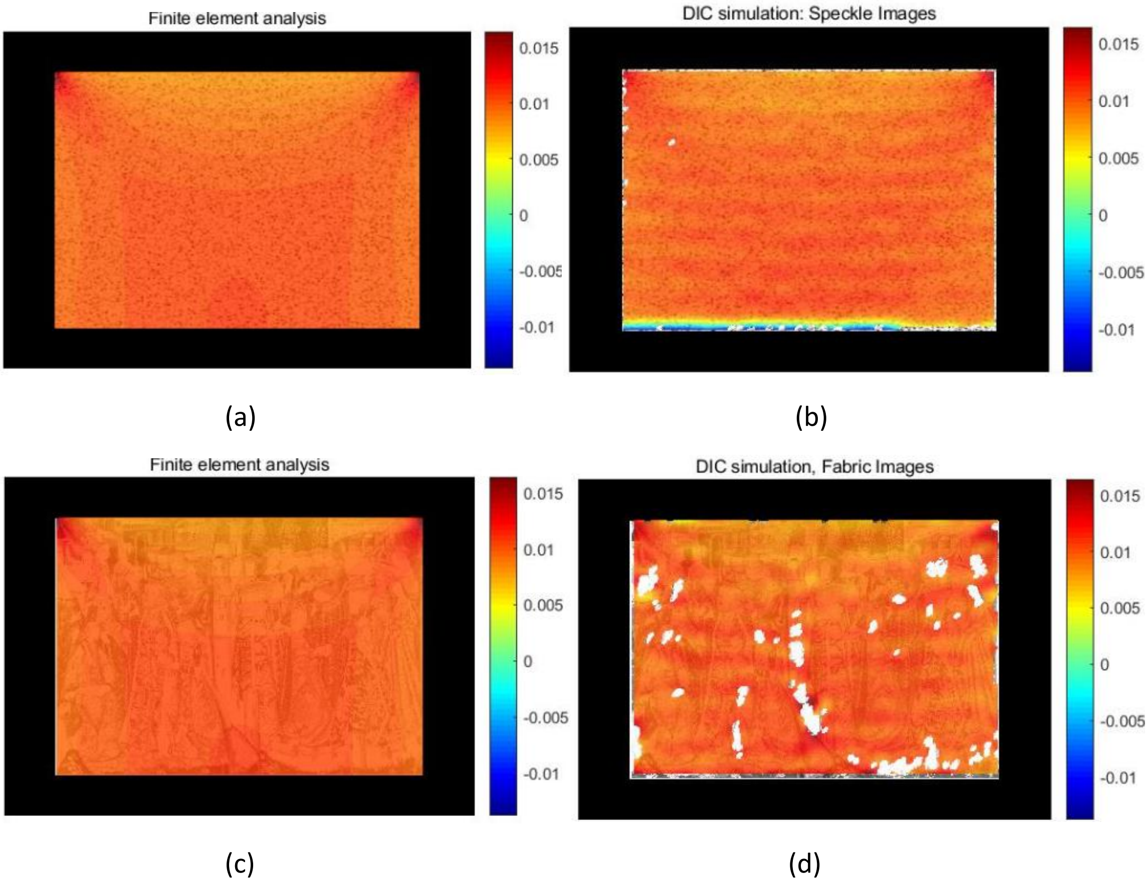


Figure 32 (a) is the stain in the brighter speckle image from FEA, (b) is the strain in the brighter speckle image from DIC, (c) is the strain in brighter tapestry image from FEA, (d) is the strain in brighter tapestry image from DIC

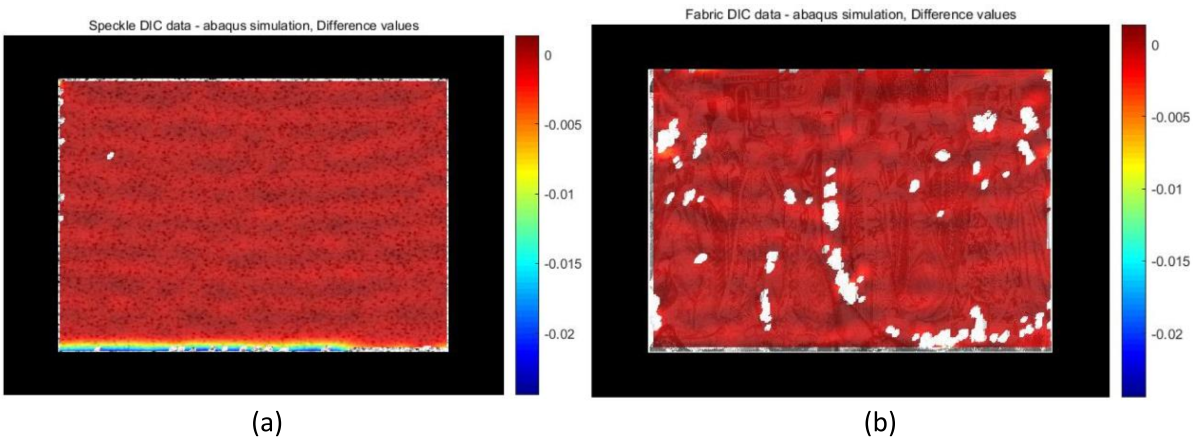
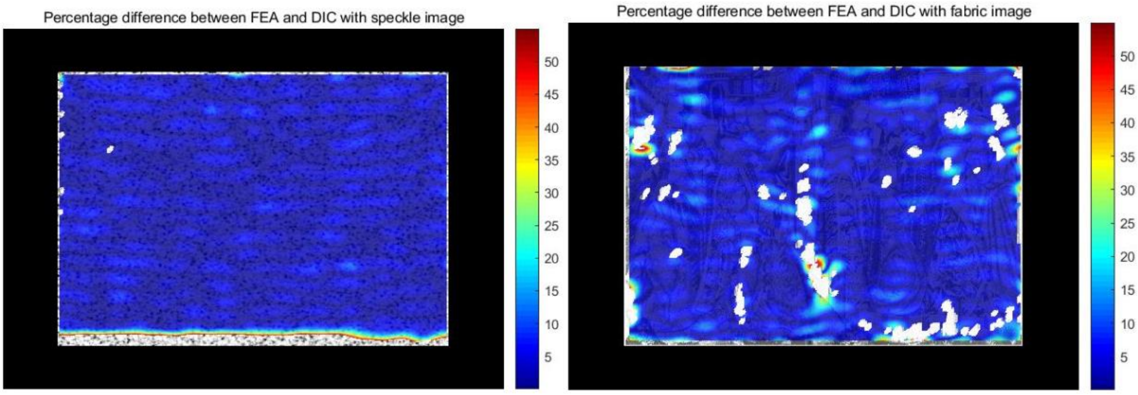


Figure 33 is the difference in strain between the DIC data and the FEA data for the speckle image and (b) is the difference in strain between DIC data and FEA data for the tapestry image



(a) (d)

Figure 34 Percent error between the FEA and DIC strain, (a) is for the speckle image, (b) is for tapestry image

By changing the brightness of the image to 40% brighter, the complicated pattern on the tapestry loses its quality. Higher brightness causing the tapestry image to lose some of its distinct patterns, therefore the DIC cannot detect the displacement. Compared to the case of 40% darker image, the strain percent error, in this case, is not completely different from the speckle image. The holes' surrounding did not register high strain completely. The global average percent error for the strain is lower compared to the 40% Darker test.

4.2.2.3 Darker Test

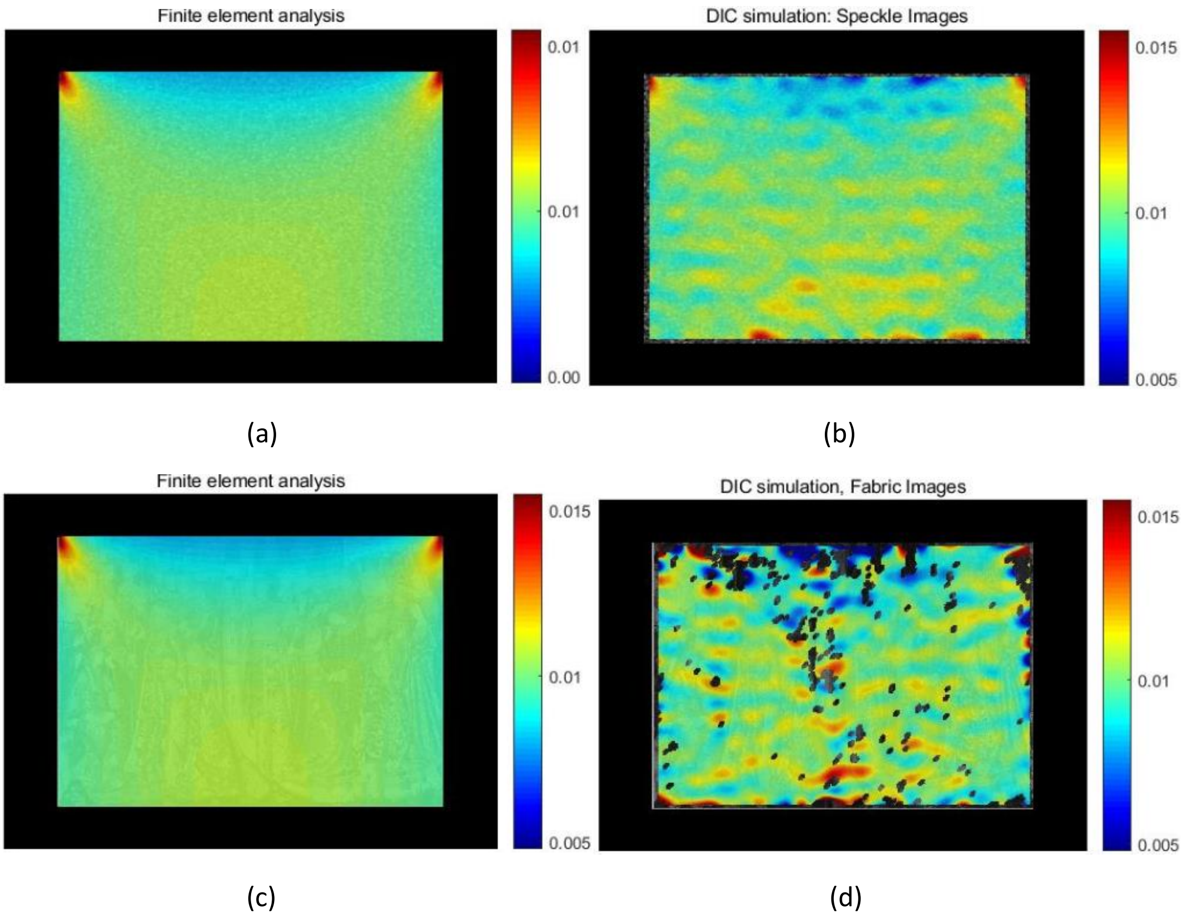


Figure 35 (a) is the stain in the darker speckle image from FEA, (b) is the strain in the darker speckle image from DIC, (c) is the strain in darker tapestry image from FEA, (d) is the strain in darker tapestry image from DIC

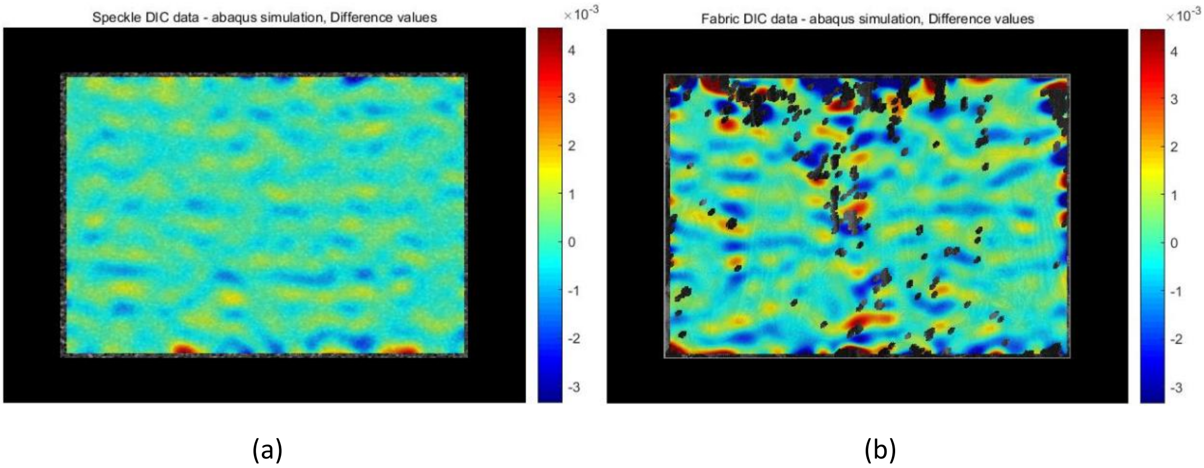
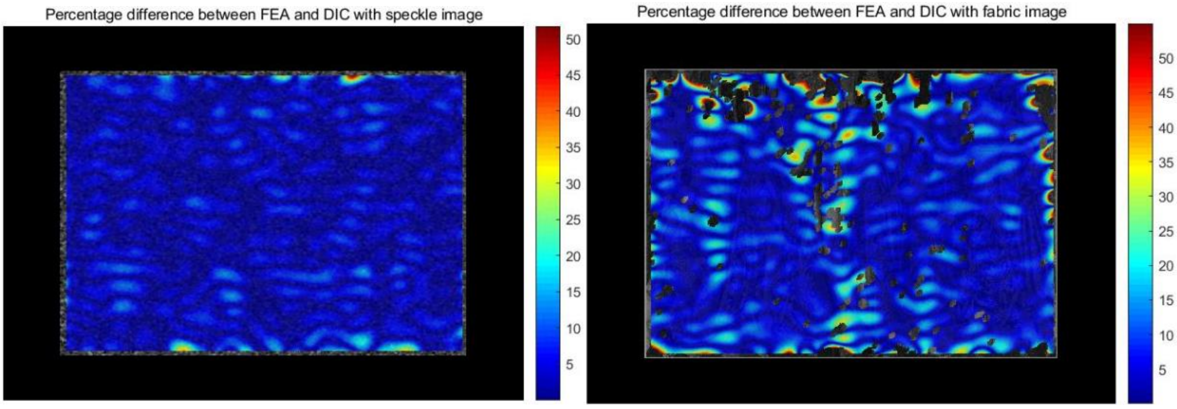


Figure 36 is the difference in strain between the DIC data and the FEA data for the speckle image and (b) is the difference in strain between DIC data and FEA data for the tapestry image



(a) (b)

Figure 37 Percent error between the FEA and DIC strain, (a) is for the speckle image, (b) is for tapestry image

By changing the brightness of the image to 40% darker, the quality decrease abruptly and more holes are introduced causing the DIC to analyse the image as if there are slit (tears). The strain, in this case, becomes different from the speckle image. Even though the speckle image undergoes the same brightness change (40% darker), it is not affected by it since the DIC can still detect the speckles' displacement. The global average percent error for the strain is higher compared to the Reference test.

4.2.3 Subset size

Analysis type	Static	Static	Static
Number of materials	1	1	1
Material behaviour	Linear static	Linear static	Linear static
Compare with speckle	No	No	No
Young’s Modulus	120	120	120
Poisson ratio	0.4	0.4	0.4
Load type	Displacement (stretching)	Displacement (stretching)	Displacement (stretching)
Time dependent	No	No	No
Stretch percent	1	1	1
Mesh density	10	10	10
Image scale	1	1	1
ROI	Whole image	Whole image	Whole image
DIC software	NCORR	NCORR	NCORR
FEA	In-built FEA	In-built FEA	In-built FEA
Deformed image	5	5	5
Subset size	21	42	84

Table 3 The setting used for the Subset Size test

(a)

(b)

(c)

Figure 38 Shows the subset size for (a) 21, (b) 42, (c) 84

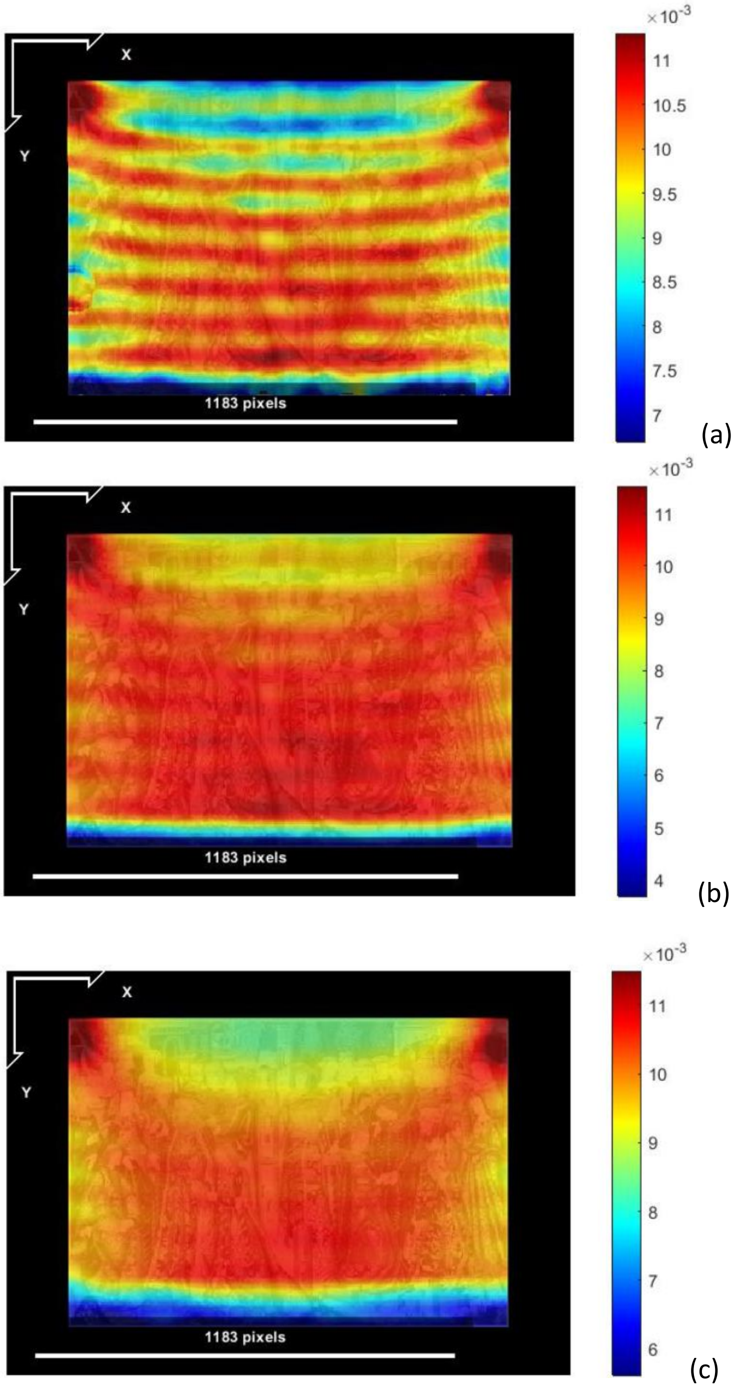


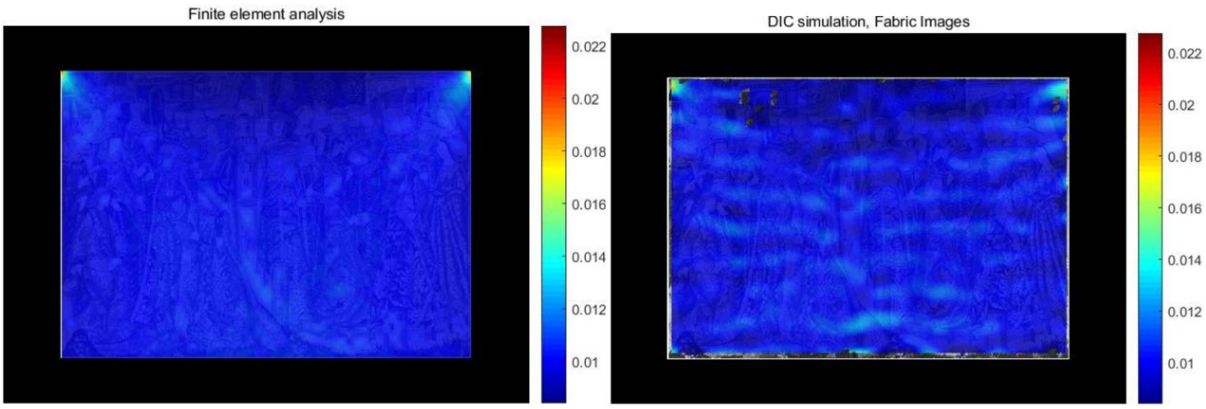
Figure 39 Shows the strain for each subset size, (a) subset size 21, (b) subset size 41, (c) subset size 84

The result for the subset test shows that the strain distribution is getting more refine (error decreases) as the subset size increase. This happens because since subset size controls the area of the image that is used to track displacement, larger subset ensures there is enough distinctive pattern contained in the area used for correlation.

4.2.4 Heterogeneity test

Analysis type	Static
Number of materials	1
Material behaviour	Linear static
Compare with speckle	No
Young's Modulus (mat 1)	120
Poisson ratio (mat 1)	0.4
Young's Modulus (mat 2)	130
Poisson ratio (mat 2)	0.3
Load type	Displacement (stretching)
Time dependent	No
Stretch percent	1
Mesh density	10
Image scale	1
ROI	Whole image
DIC software	VIC-2D
FEA	In-built FEA
Deformed image	5
Subset size	21

Table 4 The setting use for the Heterogeneity test



(a) (b)

Figure 40 (a) is the strain from FEA and (b) is the strain obtained from the DIC

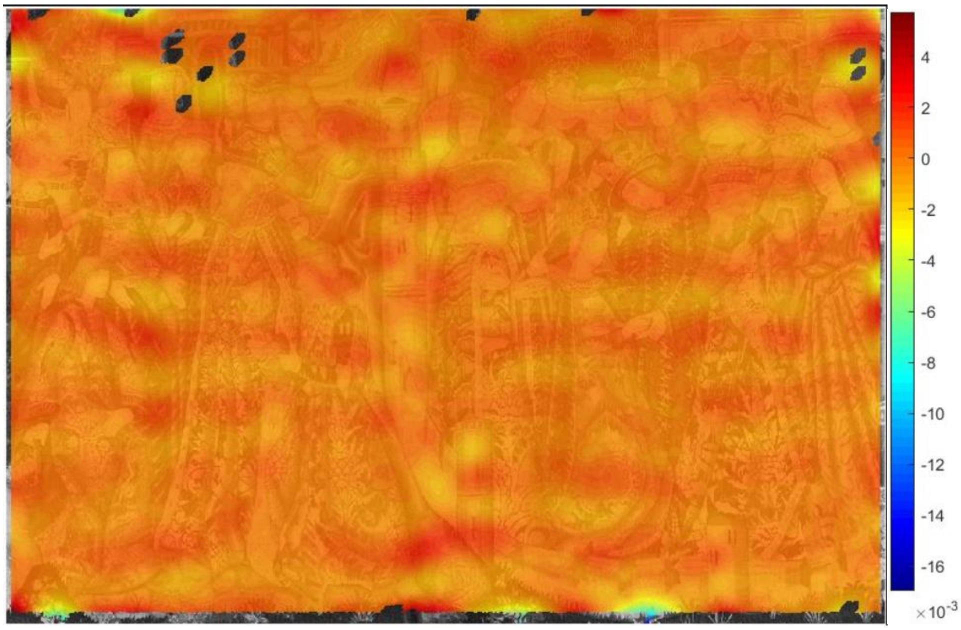


Figure 41 Difference between DIC strain and FEA strain

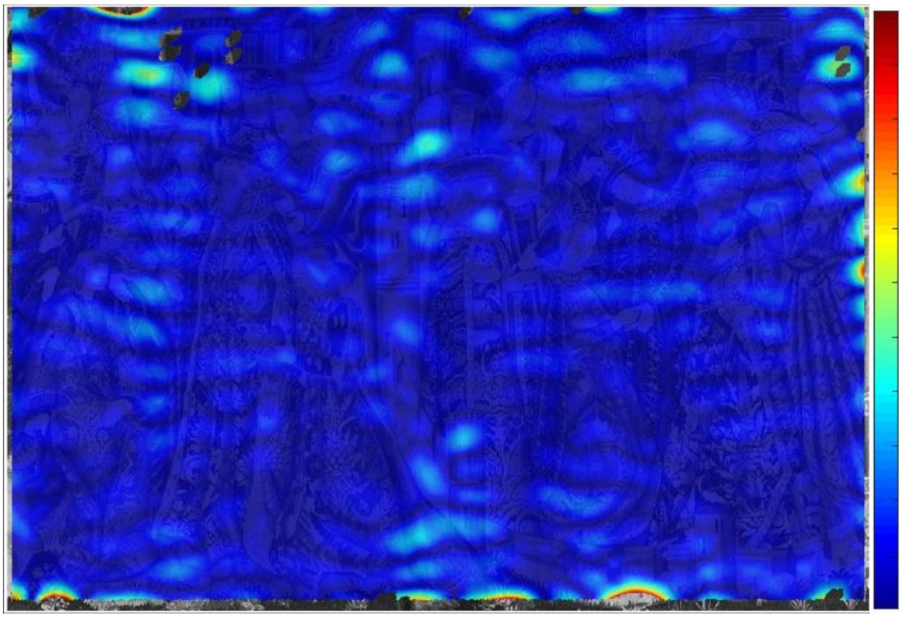


Figure 42 Percent error for the difference in DIC strain and FEA strain

The introduction of second material into the tapestry results in higher strain across the tapestry due to increase in heterogeneity and complexity. The result can be compared with the Mesh Density 10/ Reference test which uses the same setting except for the number of materials.

CHAPTER 5

5 CONCLUSIONS

From this study, the results show that smaller mesh density is important in getting an accurate result. In further research, it is better if the user can have access to ABAQUS software so that they can use the smallest number of mesh density as possible. As for the brightness of the tapestry image, it is important to have a well-lighted surrounding to take the picture of the tapestry so that the DIC can detect the displacement well. The subset size is also important especially for large tapestry with a less distinctive pattern. The user needs to predict the best size to use so that enough information is contained in each subset for the correlation. In further research, more test needs to be done to test the heterogeneity of the tapestry. Slits and patches must be included to imitate a real tapestry used for conservation process. As a conclusion, the DIC is a good method to help in the conservation of historic tapestry since it is non-destructive and cheap but extra precaution must be considered.

References

[1] Alsayednoor, Jafar & Harrison, Philip & Dobbie, Maggie & Costantini, Rosa & Lennard, Frances. , "Evaluating the use of digital image correlation for strain measurement in historic tapestries using representative deformation fields," *Strain: An international for experimental mechanics,* vol. 55, no. 2, 2019.

[2] Campbell, Thomas P, "Tapestry in the Renaissance: Art and Magnificence," Metropolitan Museum of Art Press, New York, 2002.

[3] P. Duffus, "Manufacture, analysis and conservation strategies for historic tapestries," University of Manchester, Manchester, 2013.

[4] F. Lennard, M. Hayward, Tapestry Conservation: Principles and Practice, Routledge Ltd, 2006.

[5] Krzysztof Malowany, Ludmiła Tymińska-Widmer, Marcin Malesa, Małgorzata Kujawińska, Piotr Targowski, and Bogumiła J. Rouba,, "Application of 3D digital image correlation to track displacements and strains of canvas paintings exposed to relative humidity changes," *Applied Optics,* vol. 53, no. 9, pp. 1739-1749, 2014.

[6] D. Khennouf, J. M. Dulieu-Barton, A. R. Chambers, F. J. Lennard, D. D. Eastop, "Assessing the Feasibility of Monitoring Strain in Historical Tapestries Using Digital Image Correlation," *Strain,* vol. 46, no. 1, 2010.

[7] Bing Pan, Huimin Xie, Zhaoyang Wang, Kemao Qian, Zhiyong Wang, "Study on subset size selection in digital image correlation for speckle patterns," *Optical Society of America,* vol. 16, 2008.