LESSONS LEARNT ON 3D PRINTING MICHELANGELO'S DAVID REPLICA

G. Tucci [1]*, M. Betti [1], B. Pizzo [2]

[1] DICEA, School of Engineering, Florence, Italy - (grazia.tucci, michele.betti)@unifi.it
[2] CNR-IBE, Institute of Bioeconomy, Sesto Fiorentino, Florence - benedetto.pizzo@ibe.cnr.it

KEY WORDS: 3D scanning & 3D printing, Dynamic Mechanical Analysis, Laboratory tests, Numerical modelling.

ABSTRACT:

This paper reports and discusses the results of some experimental investigations carried out with the aim to identify the best conditions for a safe exposure of the 3D printed large-scale replica of Michelangelo's David during its exhibition in the Italian Pavilion of the Expo 2020 Dubai.
The whole project posed numerous challenges due to the dimension of the Michelangelo's David (which is over seven metres high and weighs more than five ton). As a matter of fact, on the one hand, no standardized procedures have been still established to define accuracy and quality of 3D printing. On the other hand, the large-scale printing opens up new issues concerning the mechanical properties requested of the printing material and the printing set-up that is necessary to ensure the stability and durability of the printed replica.
After a general picture of the whole project, thermal characterization of the material used to print the replica and mechanical tests of samples obtained form the replica are reported and discussed. Thermal characterisation showed that the stiffness of the material was strongly influenced by temperature and that it decreased continuously as this parameter increased. Mechanical tests showed a brittle behaviour, with a collapse load approximately 10 times higher than the internal loads resulting from the self-weight alone.
The analyses here presented constitute some of the groundwork carried out for the realisation and installation of the 3D printed replica of Michelangelo's David. This conceptualisation, considering both the extreme environmental conditions and the large-size of the replica, has been particularly challenging and the adopted procedure was useful to verify the different phases of the realisation of the replica.

1. INTRODUCTION

A 3D printed replica of Michelangelo's David, re-produced with the use of scanning technology, has been the core of the Italian Pavilion in Dubai whose theme was "Beauty connects people" which echoed the general theme of Expo 2020 which was "Connecting minds, creating the future". The installation at the Expo venue has been the culmination of months of hard work that brought together teams spanning disparate disciplines, including academics, 3D scanning experts, 3D printers and art restorers. And that was very much the kind of "alliance" behind this project that has linked technology to history (Tucci et al. 2021a, 2021b, 2021c).
The project posed numerous challenges, not least due to the scale of the original which stands at over seven metres tall and weighs more than five tons. Scanning this iconic sculpture took two people 10 days to complete. Two Hexagon technologies, the AICON scanner and the Leica Tracker Scanner, were used to ensure optimum accuracy while managing the scale of the challenge.
Nevertheless, there were a number of additional challenges to overcome. For example, an 80 cm distance was required between the scanner and the statue to achieve optimum detail. This was particularly tricky when trying to capture intricate parts. Additionally, given the height of the David the scanners had to be mounted on a stair and raised, after which the team would analyse the picture to check for resolutions and accuracy, and repeat if necessary.
Following the scanning phase, printing of the David took 160 hours resulting in the 460 kg model. Once mounted on its base the replica David weighs less than 900 kg, compared to 5 tons of the original (Borri and Grazini, 2006). The statue was split into 14 segments in order to make the print possible. This was not only to make the scale manageable for the printing technology but also to ensure the strength of individual parts. Nevertheless, the resilience of each part was tested and some, such as the ankles, required extra reinforcements to be added inside. The final replica is made of Dimengel, a UV light sensitive gel, waste-free material. After printing, a clean mix of marble powder and resin was applied to give a team of restorers a thick layer to model the details, using a 3D replica as well as photos and images.
As a matter of fact, 3D digitization and printing of Cultural Heritage Artifacts (CHA) is becoming increasingly widespread (Ackea et al., 2021; Balletti et al., 2017) as it allows for dissemination, conservation, preservation, and even engagement, education, restoration and preservation (Adami et al., 2015; Bitelli et al., 2021; Domaneschi et al. 2021; Tanganelli et al. 2021). However, despite the recent developments, and the interest of both the scientific community and stakeholders, the methodology is still far from reaching its full maturity and several aspects, first and foremost of a technical nature, still need to be investigated (Bonora et al. 2021; Malik et al., 2021; Scopigno et al., 2017).
To summarize, on the one hand no standardized procedures have been still established to define accuracy and quality of 3D printing. On the other hand, the printing of large-scale CHA opens up new issues concerning the mechanical properties requested of the printing material and the printing set-up that is necessary to ensure the stability and durability of the printed replica.

* Corresponding author

With the aim of providing an insight into these aspects, this paper reports and discusses the results of some experimental investigations carried out with the aim to identify the best conditions for a safe exposure and reproduction of the 3D printed large-scale replica of Michelangelo's David during its exhibition in the Italian Pavilion of the Expo 2020 Dubai. The material used to print the replica was thermally characterised, and samples of the replica were mechanically tested in laboratory to estimate their ultimate load.

The analyses here presented constitute some of the groundwork carried out for the realisation and installation of the 3D printed replica of Michelangelo's David. This conceptualisation, considering both the extreme environmental conditions and the large-size of the replica, has been particularly challenging and the adopted procedure was useful to verify the different phases of the realisation of the replica.

In the following, first a general picture of the whole project is reported and subsequently the preliminary experimental activities are discussed.

2. THE SCULPTURE

Michelangelo Buonarroti began to make David – the symbol of Renaissance art in Florence and universally acknowledged as one of the most representative works of Italian art – in 1501.

Buonarroti adopted the figurative model of ancient Greek sculpture, passed down by the marble copies of the Roman era, using this syntax to represent the myth and exalt the hero, and give the image rhythm and balance.

Michelangelo bent his evident and at the time innovative reference to the harmony of the Greek canon to the perspective of what was to be the original position of the work, high up on a buttress of the apse of the cathedral of Santa Maria del Fiore. David communicated the civil values of freedom and the fight against tyranny on which the Republic was founded.

Once the work was completed, in 1504, the Republican government and the Gonfalonier of Justice, Pier Soderini, had the sculpture placed in the communal palace of Palazzo della Signoria. In August 1873, Michelangelo's sculpture of David left its original position in Piazza della Signoria to find its final place of rest and protection in the tribune of Galleria dell'Accademia, designed by architect Emilio De Fabris and still under construction at the time.

The new museum would open to the public in 1882.

Taken out of its context and freed from its ties and interaction with a place so packed with monuments and symbols, the political meaning of the work waned, put into the shade by the beauty that is at the basis of its fame and fortune.

3. THE RE-PRODUCTIONS

Reproductions of original works have been made since very ancient times. The Romans, who loved the "Greek lifestyle", created a very efficient system of rational methods to reproduce Greek bronze works, making great quantities of replicas.

In the past, making copies was considered a way of putting models into circulation. In the historical and social context, originality was not such a prized value, while *techné*, the ability to make or do, was. Copyists were substantially artists, and the artists we now consider the Renaissance greats were copyists too. Many replicas of the sculpture of David began to be made in the nineteenth century. So, the basis for the digital reproduction of plastic works was set in the nineteenth century with the use of casts. These, however, are now banned by the Cultural Heritage Code.

Digital technologies are changing our approach to conservation of the heritage. In recent years, top research teams have carried out numerous studies on Michelangelo's David. (Levoy et al., 2000).

Through 3D models, the "re-production" of a sculpture can be made without coming into contact with the work itself. What is more, owing to their accuracy there will be no differences between the reproduction and the original. The models' added value lies in the wealth of information they contain, which is linked to different factors and can be accessed according to requirements, like in a hypertext.

The creation of reproductions of the digitization of works, is of enormous importance not only for the conservation of works of art, put at risk due to natural passing of time or reckless human actions but also for preserving the memory of certain contexts that no longer exist.

Nowadays, we do need to encourage a reflection on the ways that digital technologies, in virtual and physical form ae changing our approach to the preservation and conservation of the material evidence of the past. High resolution digital recording and long-term secure archiving are the parentheses that are shaping this debate. If an object is recorded correctly, it can be analysed, studied, shared and rematerialized for a variety of purposes. (Lowe et al., 2020)

4. FROM DIGITAL TWIN TO PHYSICAL COPY

The term digital twin refers to a virtual representation or simulation of a physical sculpture in a digital format which captures the visual and potentially other sensory aspects of the artwork. For example, all the data needed to simulate the behaviour of the structure and the materials in the event of seismic stimuli and variations in the environmental conditions are linked to this model.

So, before the physical reproduction is made, once the digital twin is created, it can be used for various purposes: scientific studies and research; monitoring, conservation, and maintenance of the original; shared online, displayed in virtual galleries, or used for educational and promotional purposes. They also offer the possibility of interacting with the sculpture in virtual reality or augmented reality environments, providing immersive experiences for viewers.

David's digital twin of is not the work of a single person but of a team. It is the symbol of collective genius which puts a new slant on the cultural heritage and brings the concept of copy up to date, giving it new meanings.

For this project the field of cultural heritage has singled out digitization technologies used in the world of industry and borrowed them for its own purposes. Thanks to this loan, the time taken to acquire and achieve high levels of accuracy is cut short.

The 3D numerical model of David is one of the most important result of this project and the best means to safeguard the memory of its sculpted forms in time.

4.1 The 3D survey

Two survey tools were used. The first is an AICON scanner, a device with a structured light sensor. It is mounted on a trestle built especially for the purpose and it projects a sequence of familiar geometrical patterns, stripes and RBG colours. At the same time, in just a few seconds two video cameras acquire the colours of the surface and project the same pattern at set angles. The scanner operates with an accuracy of 3 to 6 hundredths of a millimetre and 146-micron resolution, inside a small window.

A second tool - a Tracker Scanner - which measures the overall volume was used to avoid mistakes when joining these partial acquisitions. This apparatus consists of a tracker combined with a laser scanner. The scanner is hand-held and moves in parallel

to the surfaces to be digitized. It acquires up to 156,000 points per second. On the other hand, the tracker exchanges a set of laser beams with the scanner which enables it to calculate the position and orientation in space.
The 3D print model derives from this ultra-high-resolution digital model (Tucci et al., 2023).

4.2 The 3D-Printed Replicas

To go from the digital model to the physical reproduction, careful research was carried out to find a latest-generation printer able to print large models at high speed.
The printer has an extruder that moves along the three axes generating one layer at a time. To do so, it extrudes a photosensitive gel which is almost instantaneously polymerized and hardened by ultraviolet light. This 3D printing procedure produced the 14 parts into which the sculpture was divided in 160 hours of printing.
While Michelangelo sculpted a block of marble using a technique that removed parts of the original material, the 3D print of David used the opposite process, progressively adding layers of material to render its exact shape and size.
The surfaces of the parts of the work produced using this technique can subsequently be finished with different materials; in this case a paste of marble dust and glues was stuck to the previously prepared printed surfaces.

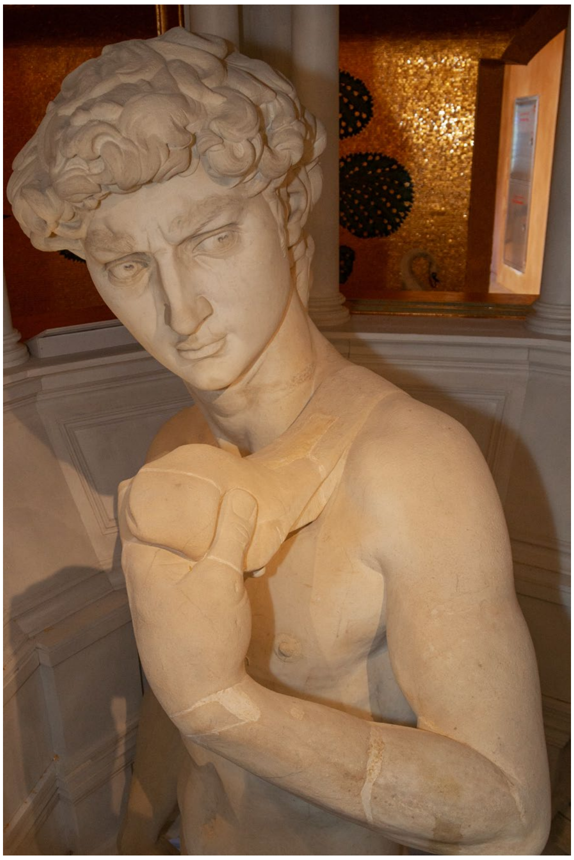

Figure 1. The Michelangelo's David 3D replica in Italian Pavilion of the Expo 2020 Dubai (detail).

Before it started to harden, great care was taken to model the paste to imitate the original on the basis of ultra-detailed photographic documentation.
The marble dust finish gave the surfaces of the work the same material appearance as the original. It even shows the signs of time, the traces left on the stone by the tools used by the artist to sculpt the work and defects and damage to the material.
Then the various parts making up the sculpture were assembled and welded together. The assembly of the portions of the work also involved the structural component.
After the delicate assembly phase, the parts still without the marble dust paste "skin" were completed. The last phase of the work was carried out by restorers who gave the surfaces their final finish.
The physical reproduction of David was placed in a moulded polystyrene "bed" designed and made so that it could be moved and shipped in safety; finally it arrived in Dubai where it was installed in the Theatre of Memory (Figure 1, Figure 2).

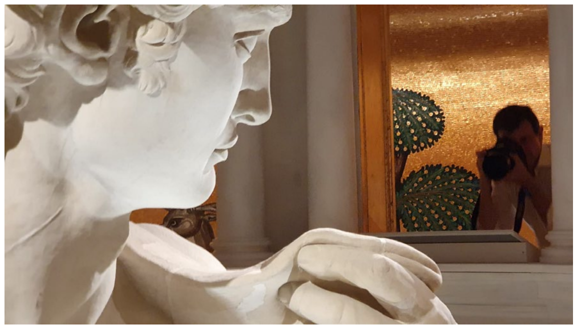

Figure 2. The Michelangelo's David 3D replica in Italian Pavilion of the Expo 2020 Dubai (detail).

5. THERMAL CHARACTERISATION

Thermal characterisation was carried out using Dynamic Mechanical Analysis (DMA), which allowed assessing how the stiffness and loss factor of the material varies with temperature (Menard, 2008). DMA is a refined technique for assessing the properties of polymeric materials. In particular, thanks to the fact that the stress applied is not static (or monotonic) but oscillatory, it is possible to evaluate the elastic (or instantaneous) behaviour of a material separately from its viscous (or delayed) behaviour. In other words, two parameters are obtained from the test. One represents the purely elastic component, and it is called storage modulus, E'. It takes into account the part of the deformation that is recovered immediately when the external stress ceases. The other parameter represents the purely viscous component, and it is called loss modulus, E". It takes into account the part of the deformation that is related to the viscous dissipation of mechanical energy in the form of heat, which cannot be recovered (Shaw and MacKnight, 2005). During the test, the temperature of the test environment can be varied so that the two behaviours described above can be evaluated as the temperature varies. Combining these two parameters, the phase shift (called loss factor or tanδ) for each point is obtained. For thermoplastics, loss factor increases with temperature to a maximum near the glass transition temperature (Tg). Tg is the temperature above which the behaviour of a material changes from predominantly glassy and rigid to rubbery and deformable (Lin, 2003).
DMA has already been used to study the viscoelastic behaviour of the polymeric materials used for 3D printing (Arunprasath et al., 2022). These studies are typically used to optimise process parameters, as in Fusion Deposition modelling (FDM) (Wang et al., 2020), or to tune the best chemical product formulation, typically in digital light processing (DLP) printing (Rehbein et al., 2021). However, these studies are usually carried out on a laboratory scale, whereas in the present case all the tests were carried out on full-scale replicas (as in the case of the

mechanical tests) or on the material actually used to produce this very large artefact (as in the case of the thermal characterisation).

5.1 Experimental results

DMA tests were carried out on Dimengel, supplied by Massivit, using DMA Q800 from TA Instruments. In particular, the specimens on which the DMA tests were carried out were obtained from the machining residues of the replica. Each sample had an approximate size of 55 x 9 x 4.5 mm^3, and the tests were performed in dual cantilever mode (span 35 mm). The test parameters were as follows (Pecoraro et al. 2019): frequency 1 Hz; strain 0.02%; rate of temperature increase 1.5°C/min.
The results of E' and tanδ are shown in Figure 3. It should be remembered that E" values can be obtained by multiplying E' by tanδ. In fact, tanδ is a dimensionless parameter, whereas both E' and E" are expressed in MPa. It is worth noting that although the storage modulus has the same dimensions as the modulus of elasticity, it is not numerically equivalent to the MOE because during the DMA test the material is stressed at very low load values to ensure that its behaviour remains linear throughout the test.
Figure 3 shows that E' was strongly influenced by temperature and decreased continuously. For example, when going from 20°C to 30°C, E' decreased by 7%, and when going from 20°C to 55°C, it decreased by more than 40%. The material started the glass transition at 44°C, while tanδ reached its maximum at 85°C. At this temperature, the value of E' was more than an order of magnitude lower than at 20°C.

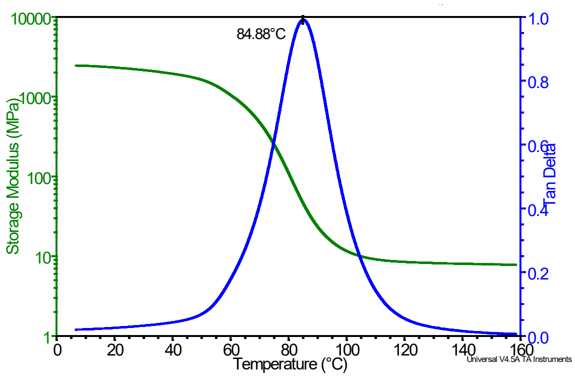

Figure 3. Values of storage modulus (E') and tanδ with increasing temperature.

However, the material regains its original properties when returned to temperatures close to room temperature. In fact, when the same tests were repeated after the material had returned to room temperature without removing the sample from the test clamp, there was a very slight increase in mechanical performance with temperature (Figure 4). However, the percentage decrease between 20 and 30°C remained at 7%, while the percentage difference between 20 and 55°C varied slightly, increasing to 37%. In addition, the material started the glass transition at 48°C and the maximum of the tanδ curve was at 89°C. This limited difference in thermal behaviour was most likely due to the loss of plasticisers present in the material due to the thermal treatment during the tests (Klähn et al. 2019). In fact, repeating the tests on a sample placed in an oven at 50°C for 21 hours, but always starting the tests from room temperature, gave a tanδ curve that could be quite well superimposed on that of the material tested twice, confirming the hypothesis (Figure 5).

However, for practical purposes, the differences found can be considered negligible, so it is safe to assume that the material will regain its original properties when returned to temperatures close to ambient.

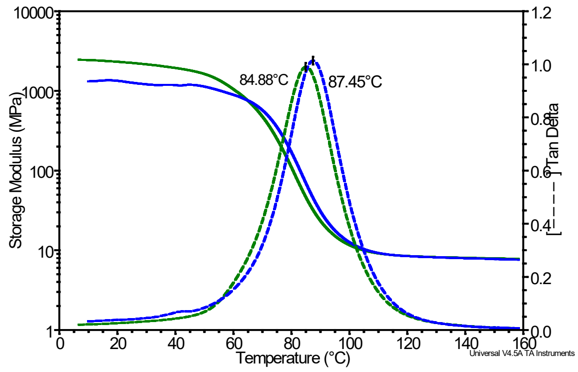

Figure 4. Comparison of the values of E' and tanδ with increasing temperature for the same sample tested twice without removing it from the clamp. Green curve: first test; blue curve: second test.

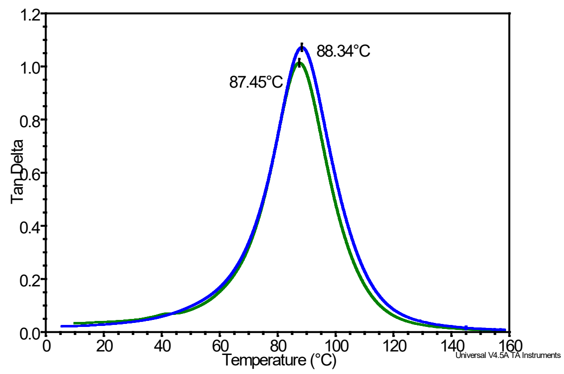

Figure 5. Comparison between the tanδ curves of a sample exposed to 50°C for 21 h (blue curve) and the sample tested twice (green curve).

6. MECHANICAL CHARACTERISATION

As a result of the Michelangelo's conception, as it is well known, David stands with one leg holding about its full weight (the right one) and the other leg (the left one) forward. Such a static behaviour, with the right leg bearing most of the David weight was clear to Michelangelo who decided to reinforce the right leg with a marble tree trunk (Borri and Grazini, 2006; Corti et al., 2015; Pieraccini et al., 2017).
Consequently, taking into account this original weakness of the statue, and considering that the printed replica of David is characterised by not being internally filled with material, an experimental campaign was carried out on the replica to evaluate the ultimate load. Specifically, mechanical characterisation was carried out by performing laboratory tests on a printing of the right leg of the replica of Michelangelo's David. The laboratory tests were aimed to assess the ability of the 3D printed replica - which does not have a solid section unlike the Michelangelo's David - to transfer the vertical loads due to the own weight.

6.1 Numerical model

The numerical model of the printed replica of David was built based on the results of the recent Laser Scanner Survey (Mugnai et al., 2021). The FE model, like the printed replica, is characterized by not having a solid section and consequently allows to estimate the tensional flow due to its own weight between the two legs.
A view of this FE model is shown in Figure 6. The numerical model was employed to evaluate the structural eccentricities to be adopted during the tests.

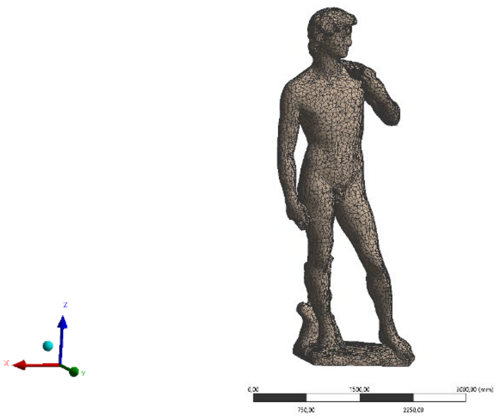

Figure 6. View of the FE Model.

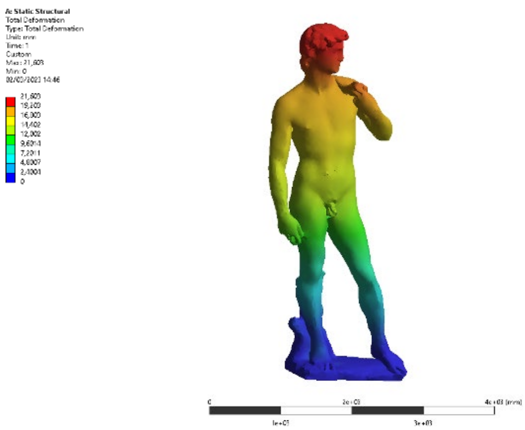

Figure 7. Displacements (mm).

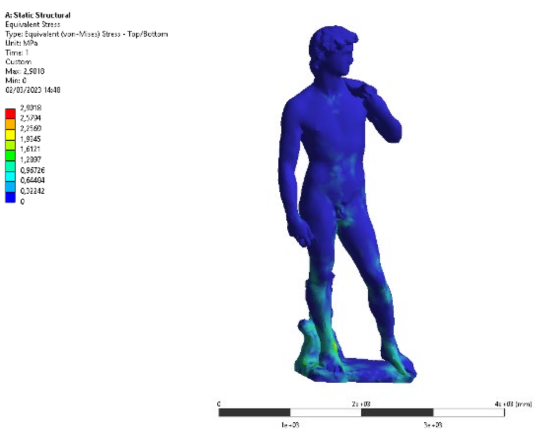

Figure 8. Von Mises Stresses (MPa).

To perform the analyses an Elastic Modulus E = 2000 MPa and a own weight γ = 1600 kg/m^3 were assumed based on the technical data sheet of the material used for printing. Numerical displacement and Von Mises stresses are shown in Figure 7 and Figure 8, respectively.
The results show that about 75% of the vertical load due to own weight is transferred to the right leg, while the left leg only draws the remaining 25%. Integrating internal stresses at the level of the ankle of the right leg it is possible to estimate the eccentricity (with respect to the centre of mass of the section of the ankle) of the axial force of about 85 and 103 mm in the x and y directions (Figure 6). These eccentricities were adopted to perform the experimental campaign.

6.2 Laboratory test results

The laboratory tests were conducted on printed replicas of the right leg of David (Figure 9).
They consisted on the application of a vertical axial load (applied at the ankle level with the eccentricities evaluated by the numerical model) until the specimen collapsed. Two types of samples were considered: one without any internal reinforcement and one with an internal net reinforcement (Figure 9). The temperature during the test was about 20°C.

Figure 9. Printed right leg of the David (w and w/o reinforcement).

Figure 10. Test layout and specimen collapse (w reinforcement).

The experimental layout is shown in Figure 10. The sample was covered with a plastic film to prevent damage in case of expulsion of material following a possible brittle collapse shows a view of the specimen with the internal net reinforcement at the end of the collapse test.

The specimen exhibited a linear elastic behaviour before collapse with a brittle behaviour (Figure 11).
By comparing the average vertical stresses at collapse (about 17 MPa for the sample without reinforcement and about 25 MPa for the sample with reinforcement) with the corresponding ones obtained with the numerical model (about 1.6 MPa) it is possible to observe that the experimental collapse values are significantly higher than those resulting from the self-weight alone.

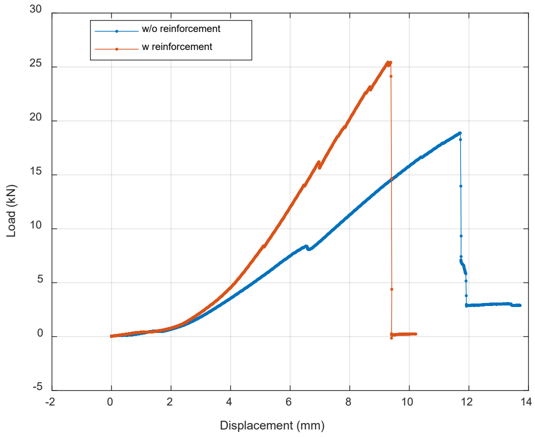

Figure 11. Load vs. displacement.

7. CONCLUDING REMARKS

The results obtained showed that the stiffness of the material was strongly influenced by temperature and that it decreased continuously as this parameter increased. However, the material regained its original properties when returned to temperatures close to room temperature. This was evident when the tests were repeated twice on the same sample. In this case, only a slight increase in mechanical performance with temperature was observed, associated with a limited increase in the peak of tanδ. This slight difference in thermal behaviour was probably related to the loss of plasticisers present in the material as a result of the thermal treatment during the tests, as confirmed by repeating the tests on a sample placed in an oven at 50°C for 21 hours.
The mechanical tests showed a brittle behaviour for both samples, with (as expected) a considerable difference in stiffness between the sample with and without the internal reinforcement. However, for both samples, a collapse load approximately 10 times higher than the internal loads resulting from the self-weight alone was observed, thus demonstrating that with a working ambient temperature close to 20° C the replica is able to assure its stability.
On the basis of the results obtained, suggestions were made for the display of the replica during its installation on the Expo site, which consisted in carefully controlling the temperature of the environment to which the replica was exposed, in order to keep it as close as possible to 25°C.

ACKNOWLEDGEMENTS

The authors want to thank the Ministry of Culture, the Italian Commissariat for Expo 2020 Dubai, Dr. Paolo Glisenti (Commissioner General for Italy in EXPO 2020 Dubai), Dr. Cecilie Hollberg (Director of the Galleria dell’Accademia di Firenze), Dr. Rosanna Binacchi (Head of International Relations for the General Secretariat of MiC) and Sig. Enzo Barlacchi (Technical Referent of the Structures and Materials Testing Laboratory of the DICEA, University of Florence)

REFERENCES

Ackea, L., De Visa, K., Verwulgenb, S., Verlindenb, J., 2021. Survey and literature study to provide insights on the application of 3D technologies in objects conservation and restoration. *Journal of Cultural Heritage*, 49:272-288. https://doi.org/10.1016/j.culher.2020.12.003

Adami, A., Balletti, C., Fassi, F., Fregonese, L., Guerra, F., Taffurelli, L., Vernier, P., 2015. The bust of Francesco II Gonzaga: from digital documentation to 3D printing. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-5/W3:9-15. https://doi.org/10.5194/isprsannals-II-5-W3-9-2015

Arunprasath, K., Vijayakumar, M., Ramarao, M., Arul, T.G., Peniel Pauldoss, S., Selwin, M., Radhakrishnan, B., Manikandan, V., 2022. Dynamic mechanical analysis performance of pure 3D printed polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). *Materials Today: Proceedings*, 50 (5):1559-1562. https://doi.org/10.1016/j.matpr.2021.09.113

Balletti, C., Ballarin, M., Guerra, F., 2017. 3D printing: State of the art and future perspectives. *Journal of Cultural Heritage*, 26:172-182. http://dx.doi.org/10.1016/j.culher.2017.02.010

Bitelli, G., Girelli, V.A., Medica, M., Tini, M.A., 2021. From 3D surveying to replica, a resource for the valorisation of museum artifacts. The case of the bas-relief of Giovanni da Legnano in Bologna. *Journal of Physics: Conference Series*, 2204:012093. https://iopscience.iop.org/article/10.1088/1742-6596/2204/1/012093

Bonora, V., Tucci, G., Meucci, A., Pagnini, B., 2021. Photogrammetry and 3D printing for marble statues replicas: Critical issues and assessment. *Sustainability*, 2021, 13(2):680. https://doi.org/10.3390/su13020680

Borri, A., Grazini, A., 2006. Diagnostic analysis of the lesions and stability of Michelangelo’s David. *Journal of Cultural Heritage*, 7(4):273–285. https://doi.org/10.1016/j.culher.2006.06.004.

Corti, G., Costagliola, P., Bonini, M., Benvenuti, M., Pecchioli, E., Vaiani, A., Landucci, F., 2015. Modelling the failure mechanisms of Michelangelo's David through small-scale centrifuge experiments. *Journal of Cultural Heritage*, 16(1):26-31. https://doi.org/10.1016/j.culher.2014.03.001

Domaneschi, M., Tanganelli, M., Viti, S., Cimellaro, G.P., 2021. Vulnerability of art works to blast hazard: The Fountain of Neptune in Florence. *Proceedings of COMPDYN 2021*. Athens, Greece, June 28-30, 2021, 1125-1134.

Klähn, M., Krishnan, R., Phang, J. M., Lim, F. C. H., Herk, A. M. V., Jana, S., 2019. Effect of external and internal plasticization on the glass transition temperature of (Meth)acrylate polymers studied with molecular dynamics simulations and calorimetry. *Polymer*, 179:121635. https://doi.org/10.1016/j.polymer.2019.121635

Levoy, M., et al., 2020. The Digital Michelangelo Project: 3D Scanning of Large Statues. *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*

(SIGGRAPH'00), New Orleans, USA, July 23-28, 2000, 131–144. https://doi.org/10.1145/344779.344849

Lin, Y.-H., 2003: *Polymer viscoelasticity: basics, molecular theories, and experiments*. World Scientific, Singapore.

Lowe, A., Mitchell, E., Béliard, N., Fornaciari, G., Tomassini, T., Damone, G., 2020: *The Aura in the Age of Digital Materiality. Rethinking Preservation in the Shadow of an Uncertain Future*. Silvana Editoriale, Milano.

Malik, U. S., Tissen, L., Vermeeren, A., 2021. 3D Reproductions of Cultural Heritage Artifacts: Evaluation of Significance and Experience. *Studies in Digital Heritage*, 5(1):1-29. https://doi.org/10.14434/sdh.v5i1.32323

Menard, K.P., 2008: *Dynamic mechanical analysis: a practical introduction*. CRC Press, Boca Raton, FL.

Mugnai, F., Tucci, G., Da Re, A., 2021. Digital image correlation in assessing structured-light 3d scanner's gantry stability: Performing David's (michelangelo) high-accuracy 3D survey. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 46(M-1-2021):463-469. https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-463-2021.

Pecoraro, E., Pizzo, B., Salvini, A., Macchioni, N., 2019. Dynamic mechanical analysis (DMA) at room temperature of archaeological wood treated with various consolidants. *Holzforschung*, 73(8):757-772. https://doi.org/10.1515/hf-2018-0235

Pieraccini, M., Betti, M., Forcellini, D., Dei, D., Papi, F., Bartoli, G., Facchini, L., Corazzi, R., Cerisano Kovacevic, V., 2017. Radar detection of pedestrian-induced vibrations of Michelangelo's David. *Plos ONE*, 12(4):e0174480. https://doi.org/10.1371/journal.pone.0174480.

Rehbein, T., Johlitz, M., Lion, A., Sekmen, K., Constantinescu, A., 2021. Temperature- and degree of cure-dependent viscoelastic properties of photopolymer resins used in digital light processing. *Progress in Additive Manufacturing*, 6:743-756. https://doi.org/10.1007/s40964-021-00194-2

Scopigno, R., Cignoni, P., Pietroni, N., Callieri, M., Dellepiane, M., 2017. Digital Fabrication Techniques for Cultural Heritage: A Survey. Computer Graphics Forum, 36(1):6-21. https://doi.org/10.1111/cgf.12781

Shaw, M.T., MacKnight, W.J., 2005: *Introduction to polymer viscoelasticity* (3rd ed.). Wiley-Interscience, Hoboken, N.J.

Tanganelli, M., Galassi, S., Viti, S., 2021. Simplified analyses for the model setting of sculptures: The "Oceano" by Giambologna. *Proceedings of COMPDYN 2021*. Athens, Greece, June 28-30, 2021, 1-10.

Tucci, G. et al., 2021a. Il David di Michelangelo nell'epoca della riproduzione digitale, *https://youtu.be/INxpV34ebk8*. Accessed 1 May 2023.

Tucci, G. et al., 2021b. O Davi de Michelângelo na era da reprodução digital, *https://youtu.be/zGZKfFdaiGk*. Accessed 1 May 2023.

Tucci, G. et al., 2021c. The digital David, *https://youtu.be/13S4tjLukBo*. Accessed 1 May 2023.

Tucci, G., et al. 2023. Recording Michelangelo's David: Ultra-High Resolution 3D Scanning and Modeling for Digital and Physical Reproduction. *Proceedings of CIPA2023 Symposium.* Florence, Italy, June 25-30, 2023.

Wang, S., Ma, Y., Deng, Z., Zhang, S., Cai, J., 2020. Effects of fused deposition modelling process parameters on tensile, dynamic mechanical properties of 3D printed Polylactic acid materials. *Polymer Testing*, 86:106483. https://doi.org/10.1016/j.polymertesting.2020.106483