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DIGITAL (RE)CONSTRUCTION FOR STRUCTURAL ANALYSIS

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ABSTRACT:

The paper investigates the advance in the most intimate understanding of the construction methods of the Fabrica Solimene (1952-1955) in Vietri sul Mare, (Campania-Italy). The aim is to increase the level of geometric and informative detail of the model, digitally (re)built by means of an indirect method using a total station survey and subsequently by means of a direct method, i.e., by importing the elaborations derived from laser scanner acquisitions and photographic data sets into a BIM authoring vector software. For this purpose, using photogrammetry, new details are acquired, specifically addressed to the study of the static-mechanical behaviour of the perimeter wall studied in its mathematical configuration of the projecting bodies from bottom to top. This study is organised on the elaboration of new clean and decimated point cloud acquisitions to be converted into volumetric models for direct use in finite element calculation (FEM) codes aimed at structural analysis. Thanks to the proposed procedure, it possible to maintain the level of geometric detail appropriate to the resolution required for the analysis. At the same time, it makes it possible to find the best pipeline to reduce the size of the model and obtain the most accurate static-structural results.

1. INTRODUCTION

Vietri sul Mare is a small town at the beginning of the rocky spur that juts out into the Mediterranean Sea dividing the Gulf of Salerno from the Gulf of Naples. The town is renowned in Italy and beyond the Alps as much to produce artistic pottery as for the amenity of the place and the climate. At this latitude, clay is purified and shaped, dried and fired in kilns to produce bricks, pignatte, tavelle, coppi, tiles and other elements used in building. Paolo Soleri (Turin 1919 - Cosanti 2013), designer of the Vietrese factory Ceramiche Artistiche Solimene, put anthropological/social reasons before tectonic necessity: function is a priority, as he defended during his apprenticeship, which began in 1947, at the studio of Frank Loyd Wrigt (1867 1959), where he held a scholarship a couple of years. When he returned to his homeland, he stopped in Vietri to learn the art of ceramics. In his early thirties, he met Vincenzo Solimene (1986-1958), one of Vietri's leading “faenzari”. To adapt production to the new commercial demand, Vincenzo Solimene commissioned Paolo Soleri to design a new factory to be built around a large furnace on the land of the “Ricciardi glassworks” (Fig.1).

The maintenance of the Solimene factory (Vietri, 54-55) has long been under discussion. The building, listed for its environmental and architectural value (G.U. no. 45 24 February 2004, s.o. 48), represents a challenge for contemporary restoration theory committed to questioning the existence of a separate issue for the recovery of the reinforced concrete skeleton. This, however, is not the only current problem.

Infill walls give stability to the whole structure and protect the interior from climatic and acoustic problems. The technical apparatus forging the main front of the Solimene factory is an exceptionally interesting case study. The solution proposed for its construction is ingenious: 18,000 amphorae forged by factory employees were used instead of the traditional hollow-case masonry (Rossi, Palmieri, 2022). Studies have ascertained the static robustness of this configuration: the bases resist well in compression, the necks in tension to build a self-supporting climate barrier (Rossi, 2017).

The amphorae, of medium size (200 x 120 mm, approximately 1 litre) are arranged tangentially to the force of gravity on the previously cast slabs together with the pillars and the concrete connecting ramp on the north side. The bases of the amphorae jut out a few centimetres from the front, while the necks are turned inwards and used to stop a steel wire that anchors them before they are finished inside the wall finished with plaster and paint.

The wall of Vietri amphorae is in fact statically robust, environmentally sustainable in terms of climate as well as economical and aesthetically pleasing, symbolically captivating and significant. In view of the urgent restoration works it was considered appropriate to develop the geometric and informative detail of the general coordination model for Historic Building Information Modelling buildings (Zhang, Zou, 2022).

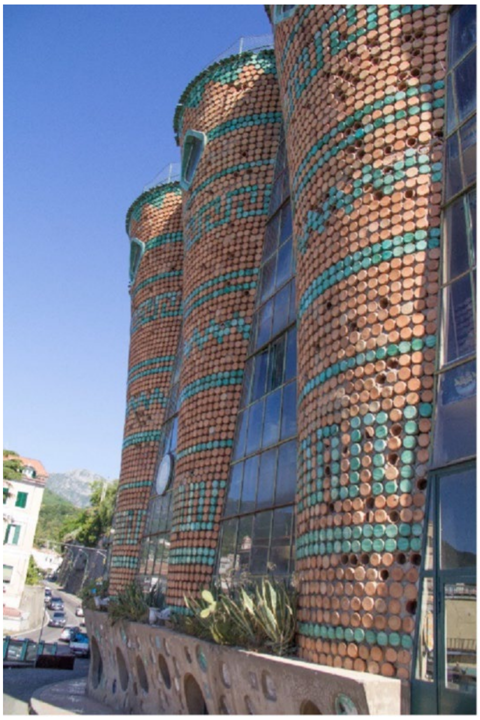

Figure 1. A view of the Fabbrica Solimene in Vietri

However, to advance a more intimate understanding of the construction methods of the “wall component”, it was necessary to supplement the survey with close-range photogrammetric acquisitions. The bottoms of some amphorae detached in the south front of the factory at human height, allowed the easy capture of photographic shots. The scans obtained by processing the acquisitions with digital photogrammetry software, to be topologically manipulable, were processed with the aid of editable 3D modelling software. This study is organised on the elaboration of new clean and decimated point cloud acquisitions to be converted into volumetric meshes for direct use in finite element calculation (FEM) codes aimed at structural analysis. The procedure makes it possible to maintain the level of geometric detail appropriate to the resolution required for the analysis. At the same time, it makes it possible to find the best pipeline to reduce the size of the model and obtain the most accurate static-structural results. The finite element analysis is based on the mathematical modelling of the properties of the basic element of the infill wall. In the literature there are approaches to generate volumetric meshes of the cleaned and decimated 3D point cloud: a) redraw with a CAD modeller (Brune et al., 2012); b) directly use the triangular mesh generated by the 3D acquisition pipeline (Castellazzi et al., 2015) c) generate a volumetric mesh from the point cloud (Bitelli et al., 2016). The use of Non-Uniform Rational B-splines (NURBS) geometries is appropriate. Basic spline curves and surfaces show the way control points and nodes work (coincident only if the curve is of prime degree). It is therefore easy to modify their characteristics based on the adaptive points of the profiles and parametrically modify them, flexibly to the density of the polygons to be converted into polyhedral elements. In fact, the computational complexity of FEA grows exponentially with the number of nodes and indirectly with the degree of the curves used to generate the simulated object. Indispensable when not opportune, a consistent simplification of the mesh associated with a topological rearrangement with retopology (Gonizzi, Guidi, 2017). The retopologized mesh is typically based on quadrangular elements (quads) that are better distributed on the surface, thus leading to a strong reduction in the number of final polygons of which the model is composed. Downstream of the retopologisation of the model, finite element analyses were developed. To this end, the results of different possible analysis approaches, which consider different types of finite elements and different mesh densities, have been critically evaluated to assess how the choices made when defining the model may influence the results of the analysis.

The objective of this work is to present suitable results to:

1) validate the method to show its advantages but also the disadvantages that the technique used tends to solve.

2) develop an integrated approach for the definition of structural element models based on the survey and digitisation of existing works, capable of reducing the modelling and computation burden of finite element analysis while maintaining accuracy and reliability of results.

The work described in the paper starts from previous research that was based on the use of laser scanning survey (Rossi, Palmieri, 2022) compared with indirect method (Rossi et al., 2020).

2. METHODOLOGY

2.1 Survey and post processing of the models

The entire façade of the Fabrica was surveyed using a Canon 60D APS-C camera with a 20mm fixed lens. Since it was a sunny day, the parameters of the camera have been set with ISO to 200 and aperture to 5. The GSD (Ground Sample Distance) and the accuracy of the model were considered to obtain a precise and accurate model and to have a value as comparison for the next steps of the pipeline. The GSD for the entire building model is 0.1 cm/pixel while for the single vases it ranges between 0.004 and 0.006 cm/pixel. More than 200 images have been acquired of the entire exterior part of the building (Fig.2).

Figure 2. The point cloud obtained through photogrammetry

Using then the same camera body but with a different optic, a 60mm macro lens, portions of the façade were surveyed relating to a 4x3 'mummarelle' block including intact and broken vases. For each single vase the images acquired ranged between 22 and 29 (Fig. 3a-b). With the survey of the broken vases visible in the façade, it was possible to acquire the interior and the thickness of the vases, while with the entire ones the basis. For the bigger portion, 58 images were acquired (Fig. 4). The 3D model was obtained with Agisoft Metashape software and scaled based on both horizontally and vertically positioned targets on the structure integrated with manual measurements since there were no chance to put marker on the structure since the owners preferred this way.

The final 3D models counted respectively around 2M elements for the broken "mummarelle", 10M elements for the 4x3 portion of the façade. All the 3D models were then post-processed to cancel any topological error (e.g., duplicated vertexes or faces, non-manifold edges, self-intersecting faces) (Fig. 5a-b).

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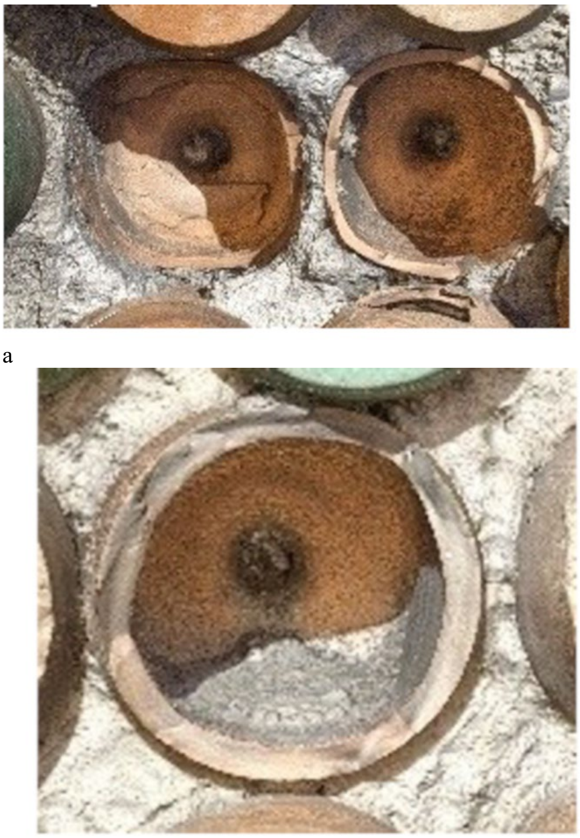


Figure 3. The point cloud of single vases acquired.

For the vases of the Fabbrica, the first step for the creation of the retopologized model was the closing of the mesh to obtain a complete shape of the vase. Using the model of the interior of the vase acquired during the survey of the broken one, it was duplicated, changed the direction of the normals, increased in dimensions using the transform tool available in Autodesk MeshMixer which allows to add an offset to the mesh, in this case calculated on the thickness of the vase measured on the model (Fig. 6a-d). After this step, the two meshes were aligned with CloudCompare and then merged, in the same software, to have a closed model. The same pipeline was followed for both broken and entire vases (Fig. 7a-b).

Figure 4. The 3D mesh of the 4x3 specimen selected for the tests.

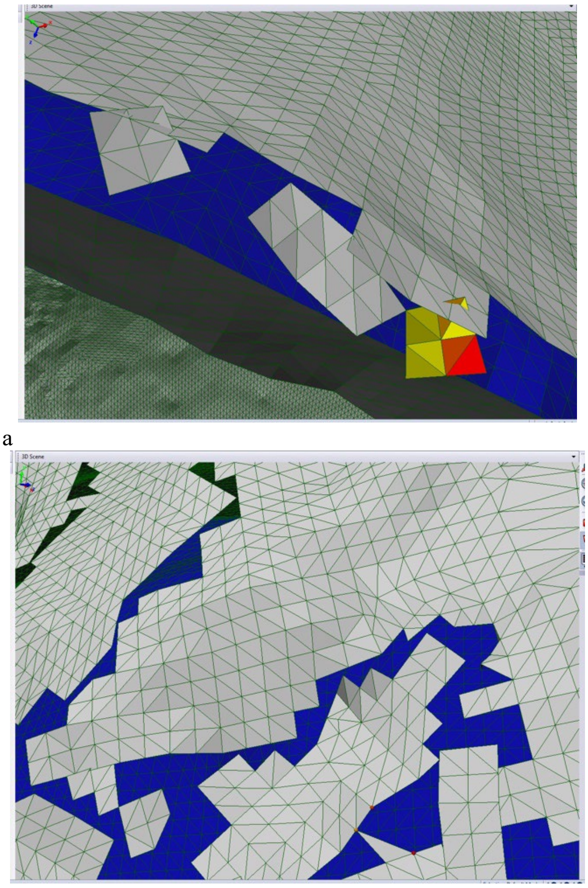


Figure 5. Examples of the topological errors corrected in the post processing operation on the retopologised meshes.

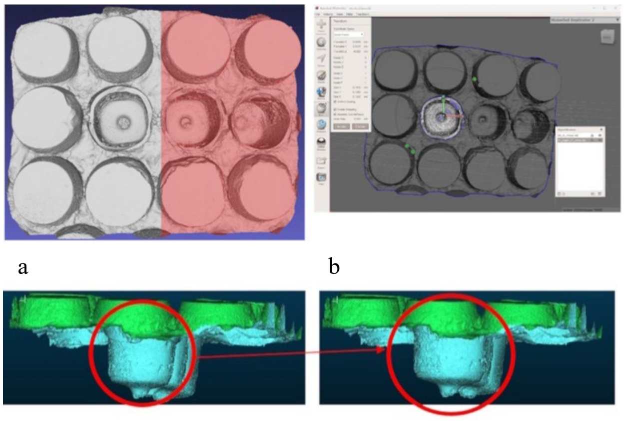


Figure 6. The creation of the outlier of the vase: The single vase was extrapolated from the model (a); it was copied and with the “transform” command enlarged by an offset calculated on the thickness of the vase (b); the difference between the model with only the interior displayed (c) and with the added exterior (d).

These final models were then simplified using retopology, which is available both in open-source packages such as InstantMeshes or Blender, or in commercial software packages such as ZBrush by Pixologic, used in this work because this software is built specifically for rebuilding the topology of the models and it has the option of projecting the retopologized model on the high resolution one, increasing the adherence of the two models[1] (Figg. 7a, b).

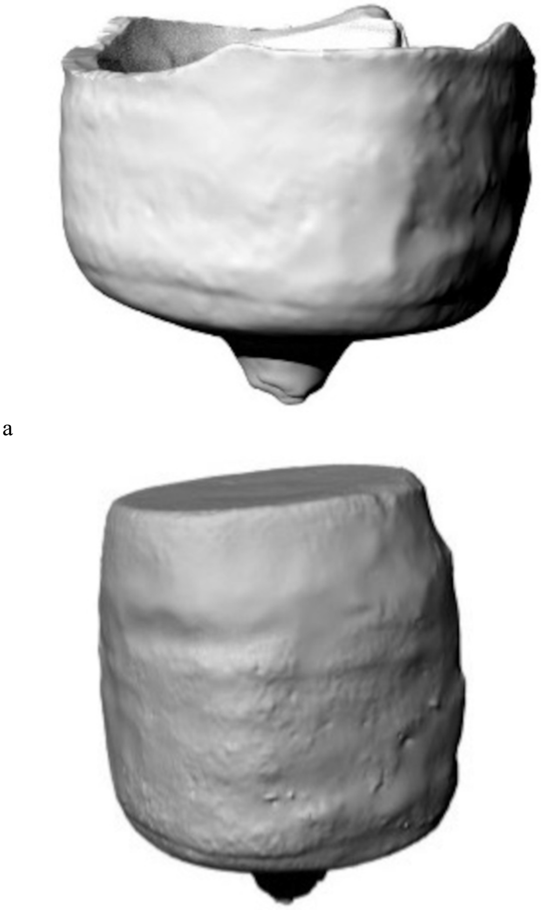
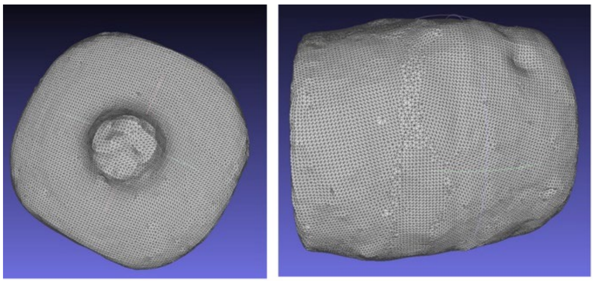


Figure 7. The vases reconstructed with interior and exterior.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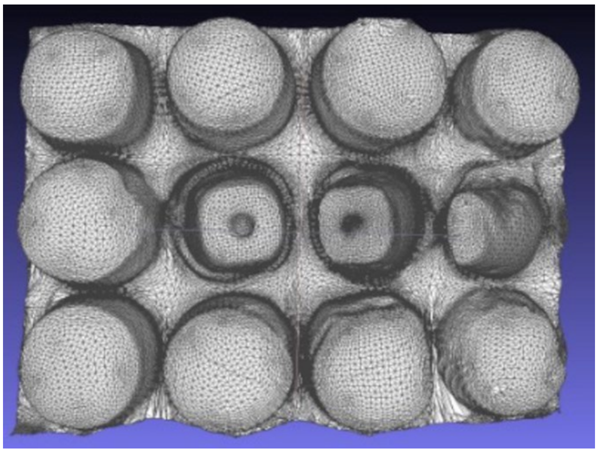
b

Figure 8. The retopologized models: the broken vase (a); the entire one (b) and the specimen of 4x3 vases, both broken and entire (c).

After the retopology, it was necessary to transform the superficial meshes in polysurfaces (NURBS) that is a mandatory passage to obtain a volumetric model suitable for FEA. A mesh represents 3D surfaces with a series of discreet faces, NURBS, on the contrary, are mathematical surfaces.
The conversion from a mesh to a NURBS is implemented in CAD software or similar (e.g., 3DMax, Blender, Rhinoceros, Maya, Grasshopper, etc.) and it transforms a mesh composed by polygons or faces to a faceted NURBS. In details, it creates one NURBS surface for each face of the mesh and then merge everything into a single polysurface. Depending on the mesh, the conversion works in different ways:

- If the starting point is a triangular mesh, and while, by definition, triangles are plane, the conversion creates trimmed or untrimmed planar patches.
- If the starting point is a quadrangular mesh, the conversion creates a 4-sided untrimmed degree1 NURBS patches, meaning that the edges of the mesh are the same as the outer boundaries of the patches.

Considering the theory, a quadrangular mesh is more suitable to be converted in NURBS[2] (Figg.8a-b). For this work, the MeshToNurb tool implemented in Rhinoceros was used that allow to directly transform a superficial mesh into a polysurface. The fundamental issue is to have a 3D closed mesh to have a polysurface ready to be exported in *stl or *step file to produce a volumetric model suitable for FEA (Figure 8c-e). The models have also been oriented to have the z axis up. This step is

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[1] The tool used was the ZRemesher palette, where there is the possibility to select the number of polygons desired and the choice of increasing the coherence of the two models. This can be done selecting the "adapt" button and increasing the value of the "adapt size" slider. This important parameter defines the polygon distribution on the model and can drastically increase the quality of the topology by giving more flexibility to the algorithm. This function defines a vertex ratio based on the curvature of the mesh. A low setting will provide polygons that are as much square as possible and almost the same size, several final polygons closer to the number set in the selection tool but can introduce topology irregularities where the geometry is much complex. A high adaptive size means obtaining polygons that are rectangular in shape to best fit the mesh's curvature and which density can vary along the mesh surface even if the program creates smaller polygons where the geometry requires. With a higher value of this parameter there is less control on the final number of desired polygons after retopology.

[2] The conversion of a polygonal model in a NURBS model is available on some CAD packages as automatic process, that in general tend to produce a higher number of small patches when the original mesh is topologically unorganized. Triangular meshes will be converted into either trimmed or untrimmed planar NURBS surfaces, meaning that the resulting polysurface will have the same edges as the original mesh model and be composed entirely of degree 1 x 1 (bilinear) NURBS surfaces. By rearranging the initial topology of the mesh, a preliminary condition for minimizing the number of NURBS patches of the converted model is set, and this represents a better starting point for the volumetric mesher embedded in any standard FEM package.

fundamental to better apply loads and constraint on the models in the FEA software.

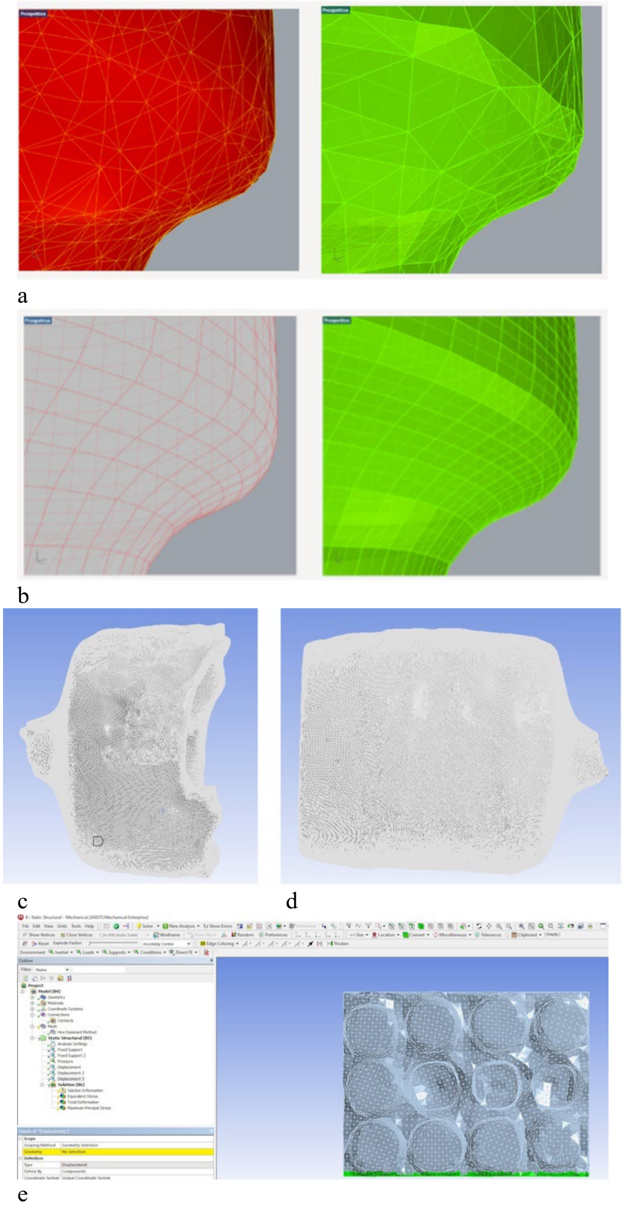


Figure 9. The comparison between a simplified triangular mesh and its corresponding NURBS (a) and the retopologized mesh with its corresponding NURBS (b). The meshes are represented in red (left side of the images) and the NURBS in green (right side of the images). The NURBS of the broken vase (c), of the entire one (d) and the 4x3 specimen (e) imported in the FEA software to be analysed.

2.2 Finite Element Analysis

The Finite Element Method (FEM) is a numerical technique used to solve engineering problems, such as static, dynamics, thermal, electrical, fluid-dynamics problems that do not have an analytical solution. Finite Element Analysis (FEA) considers the definition of a mathematical model, which is an idealization of the physical object, and is built to simulate its structural behaviour under the action of prescribed loads or conditions. The analysis is then carried out on the models meshed using given elements, which can differ with respect of the dimension of the problem of interest (2D or 3D), or also with respect of the order of approximation of the displacements of the nodes of the elements with respect of the displacements of the material points.

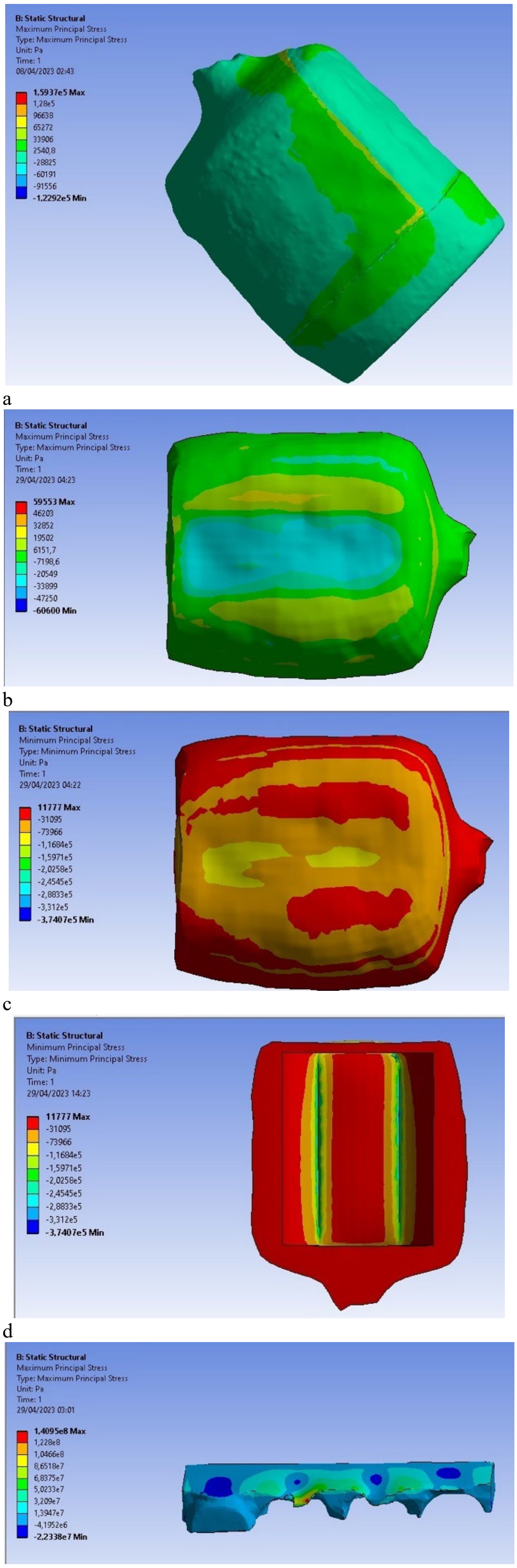
In a structural model, FEM allows detailed visualization of the severity of the stress state and of the critical points of the structure on the base of the distribution of stresses and displacements. In the present paper, the static/structural analysis has been performed on different models giving different load and boundary conditions that comes from a first approximation of the loading condition of each single case (Tab.1):

1. Single vase complete: the model of the entire mummarella has been cut in two parts, simulating the position of the vase on the façade with the bottom few cm outside the structure.
2. Single vase cut in half, to simulate the real shape of the mummarella. The void inside the model was created duplicating the 3D mesh, reducing its measures considering the exact thickness and performing a boolean difference between the two models.
3. A portion of the wall consisting in 1 entire amphora and 3 broken, cut in a half to simulate the shape of the wall.
4. The 4x3 specimen abstracted and simplified, meaning that there is no real shape of the vases, and their geometry is only superficial, while the interior or the wall is full.

Model	**Buondary Conditions**	**Load**
Entire Mummarella	Fixed support in the middle and below	-30000 Pa on z axis
Entire Mummarella, cut	Displacement free on z axis; fixed support in the centre	-30000 Pa on z axis
One single line of 4 vases, cut	Displacement free on z axis, two displacement one each side free on x axis	-10000000 Pa on z axis
4x3 Specimen	Displacement free on z axis, two displacement one each side free on x axis	-10000000 Pa on z axis

Table 1. Boundary conditions and load for each model.

The free displacement on x and z axis simulate a symmetry condition, allowing the software postulating that the model is not finished as displayed. As for the material properties, for the models of the mummarella, Young Modulus, Poisson Ratio and density of clay have been assigned, while for the portion of the wall, a mean of clay and mortar properties has been assigned. Results can be seen in Figg. 10a-e. The analysis gives a good result regarding the stress distribution in the vases and giving an idea of their capacity to sustain loads. It is, indeed, a very simple analysis whose importance is related to the possibility to directly use the 3D reality-based models in FEA and to a first interpretation of the static behaviour of the structure.



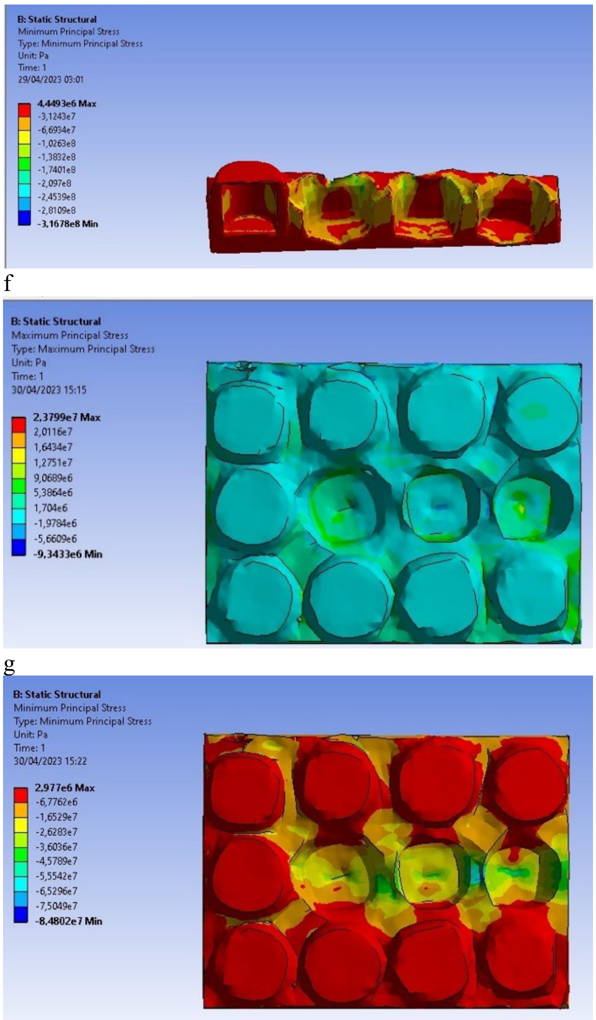


Figure 10. The Max and Min principal stress calculated on the different models: (a) entire mummarella; (b-d) entire mummarella, cut; (e,f) the single line of vases; (g,h) 4x3 sample with mean calculation of material parameters.

3. RESULTS

In the literature, several approaches have been used to generate the volumetric mesh from the 3D point cloud acquired by reality-based technique: a) redraw with a CAD modeller a new model starting from the 3D mesh [Brune et al., 2012]; b) using the triangular mesh obtained from the 3D acquisition [Castellazzi et al., 2015] c) generation of a volumetric model directly from the 3D point cloud [Shapiro et al., 2011; Bitelli et al., 2016]. The use of retopology and the proposed method showed excellent performance using a reality-based model for FEA. The use of 3D measurement uncertainty as a simplification criterion allowed to significantly reduce the mesh size while maintaining high accuracy of the simplified model compared to the high-resolution one [Gonizzi, Guidi, 2017]. The retopologised mesh is based on quadrangular elements The organisation of polygons in the retopologised models allows for a better distribution of elements, thus leading to a strong reduction in the number of final elements composing the model. The proposed method is based on a skilful use of retopology techniques, combined with the transformation of the retopologised model into a mathematical one of NURBS surfaces, as close as possible to the real shape of the object surveyed, but suitable for being transformed into 3D volumetric models into FEM packages. The conversion of a polygonal model into a NURBS model is available in some CAD packages as an automatic process, which in general tends to produce more small patches when the original mesh is topologically unorganised. By rearranging the initial mesh topology, a precondition is established to minimise the number of NURBS patches in the converted model, and this provides a better starting point for the volumetric meshing incorporated in any standard FEM package. Although retopology adds smoothing to the simplified tessellated surface, the reorganisation of the square elements on the surface avoids sharp artefacts, non-manifold edges and allows for model simplification while maintaining the accuracy of the high-resolution model. The comparison made in CloudCompare between the retopologised mesh of the entire mummarella and the high-resolution one (Fig. 11a) and between the retopologised mesh and the 3D CAD surface created from the profile extrapolated from the photogrammetric models shows the differences in standard deviation of the two models (Fig.11b).

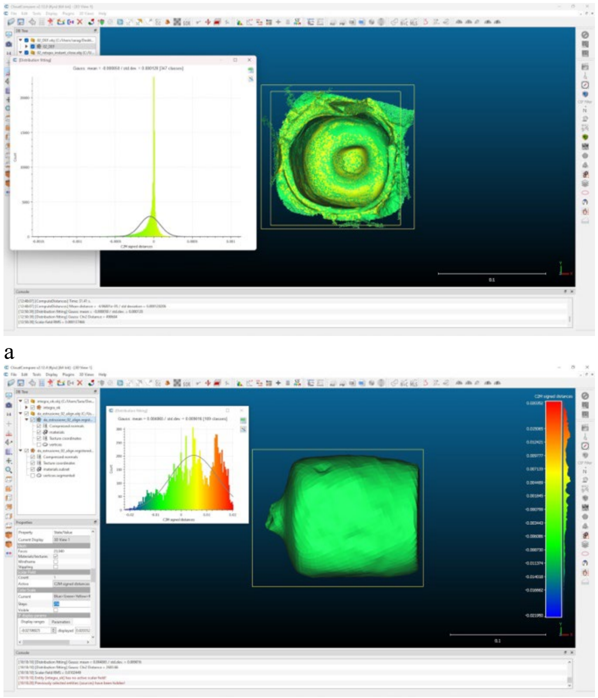


Figure 11. The comparison between the high-resolution photogrammetric mesh and the retopologized one (a) and between the retopologized and closed mesh and the CAD reconstruction from profile (b).

The results indicate that the retopologised models are closer to reality than the drawing of the model from scratch, even if the starting point was a profile directly extrapolated from the photogrammetric model and even considering the strong post processing of the initial models to have a complete one of the surveyed artifacts. The standard deviation obtained in the second comparison (CAD vs. retopology) yielded more than 9 mm, while the first (high resolution vs. retopology) yielded approximately 1 mm. The combined effect of the decimation and feature preservation capabilities of the instant alignment algorithm makes it one of the best candidates for simplifying the use of reality-based models for FEA.

The main bottlenecks on which the process run into were mainly concerned the post processing part, starting from the simplification of the mesh to the creation of volumes. Not to mention the difficulties and the long process in fixing all the topological problems the meshes have, both triangular (from the survey) and retopologized, the other main issue regarded the effective creation of a 3D volumetric model which was as close as possible to reality without losing accuracy and geometrical detail.

The 3D photogrammetric mesh, in fact, is per se formed by a triangular surface which describes the shape of the object surveyed. It does not have information on the inside of the object. So, the volumes obtained through all the passages explained in this paper did not correspond to the real shape on the interior of the wall, meaning it did not have the description of each vase encapsulated in the mortar to create the shape and the geometric information of the wall of the Fabbrica. This is the reason why different tests were done on different models, the volumes as-is, directly obtained through the pipeline described and the volumes created intersecting and subtracting the models to obtain a final model closer to reality. Of course, it is not possible and probably is not even useful to replicate these passages on the entire model.

The static structural analysis done meant to validate the possibility in using the 3D reality-based models directly in FEA to consider the future application starting from the 3D model as an input for a more detailed one. This means the use of the results obtained on the entire model as load conditions applied in correspondence to the details obtained through different monitoring techniques such as tomography. This process can be considered as the first step in the utilisation of the simplified reality-based models as a mean in the definition of constitutive laws for equivalent materials, such as demonstrated for example in Abdulla et al, 2017; Rehman et al., 2019).

4. DISCUSSION AND FUTURE WORK

The surveying techniques made it possible to detail with a certain coefficient of error (admittedly minimal for buildings) a model that, although unstructured, returns real measurements and textures. To manipulate the reconstructed components on the digital construction site, however, it is necessary to have an information structure adequate for the high level of geometric detail. Bringing the procedures of the digital assembly processes to the executive level for control while maintaining the accuracy and reliability of the results is the goal of the workflow organised for the Solimene factory. In this scenario, the survey of the wall thickness anticipates and reflects on the quality of the mechanical characteristics that are shared and interoperable within the general model, looking at the opportunity of an interdisciplinary work within which each one, empowered in a different way, intervenes with its own specific skills.

The next steps will involve applying this methodology to a segment between the pillars and the two storeys and the everted facade and comparing the results of the analysis with those of a common masonry wall, to define the material specifications as those available in BIM software such as Revit for common brick walls. The means of this procedure is to bring to an executive level within the limits of the classification in force in Italy (UNI 11337) with the ultimate aim of controlling the procedures of digital assembly processes to manage project communication for diagnostic purposes and develop an integrated approach for the definition of models of structural elements based on the survey and digitization of existing works, able to reduce the modelling and calculation burden of finite element analysis while maintaining the accuracy and reliability of the results.

The assembly of the individual amphora bottles used and positioned as in the real wall within the general coordination model has allowed us to direct the study on the material and technological characteristics of the wall component. the opportunity is seized thanks to and by virtue of the different information speeds that allow the organization into development levels (Lod) of the model implemented and promoted by the law in force in Italy. It persists in the Italian standard (Brusaporci, Maiezza, 2016, p.58). The conceptual distinction already introduced in the rules adopted in the United Kingdom England (PAS 1192-2 of 2013, Historic England, 2017) between the Level of Geometry (LoG from reliability from Level of Information Needed (LoI) not only persists but is more articulated to make the geometric model more "elastic" and therefore the information model is equally necessary in the complete work process, according to the BIM method. Consequently, the aggregation model of functioning components governs knowledge through the underlying database the thematic organization allows consultation at different levels confirming the global model as a collector of what is known in every field. on the product a need that has always been felt but which only today digital technologies allow to make operational

In this perspective, the integrated survey placed at the origin of the shared and interoperable workflow looks at the opportunity of sharing a personalized library of 3D objects, for us the mummarella, parametrically variable not only in shape but in material and technical consistency, which can be extended if desired to any other type of archived data - to be used inductively for restoration and maintenance projects of the Solimene factory but also in other cases to digitally manage construction processes (UNI 11337:2017), i.e. the wall of amphorae with high physical mechanical functional climatic aesthetic communicative qualities (Mansuri et al, 2022).

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