X International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2021
K.-U.Bletzinger, E. Oñate, R. Wüchner and C. Lázaro (Eds)

LAST WITNESS AND DIGITAL TWIN – PHYSICAL AND DIGITAL MODELLING THE MUNICH OLYMPIC SPORTS HALL – A CASE STUDY

Baris Wenzel[*], Eberhard Möller[*], Benjamin Schmid[†], Christiane Weber[†]

[*] Karlsruhe University of Applied Sciences,
Moltkestraße 30, D – 76133 Karlsruhe
e-mail: baris.wenzel@h-ka.de, web page: http://www.h-ka.com

[†] Universtiy of Innsbruck,
Technikerstraße 21, A – 6020 Innsbruck
e-mail: benjamin.schmid@uibk.ac.at, web page: http://www.uibk.ac.at

Key words: physical models, measurement models, spatial structures, structural design, structural modelling, digital twin, Munich Olympic roofs.

1 INTRODUCTION

In the 20th century, innovative constructions were often developed and analysed with the help of measurement models. Most of such physical models are lost today. Of the filigree measurement models for the Munich Olympic roofs, that one of the sports hall remains as one of the last witnesses. This model is focused by a case study within the sub-project "Last Witnesses" of the priority program "Cultural Heritage Construction" of the Deutsche Forschungsgemeinschaft. Beyond this background the paper illuminates in a case study more precisely the planning of the roofing for the sports venues of the 1972 Summer Olympics in Munich, examining in detail the importance of the measurement models, especially for the sports hall, and the role of the various participants in the project. As part of the study, a digital twin was generated. This parametric 3D model can be used for multiple purposes all over the field of civil engineering as simulating adaptations of loads by mutable factors like caused by climate change or to establish the history as an independent subject of research and teaching in the faculties of civil engineering and for organizing exhibitions or even museums about the works of civil engineering[1].

Figure 1: Surviving model of the Olympic sports hall

2 PHYSICAL MODEL

2.1 Olympic roofs Munich

For the sports facilities of the 20th Summer Olympic Games, which took place in Munich in 1972, an architectural competition was announced in 1967. The architectural office Behnisch + Partner won this competition with their vision of light, transparent roofs for the stadium, the sports hall and the swimming pool. These roofs had to cover an area of approximately 74,000 square metres. The first design, which was visualised with a model made of tulle, was finally realised between 1969 and 1972 as a pre-tensioned cable net construction. The shadeless, transparent roofs were intended to enable television broadcasting on the one hand and to represent an open and democratic Germany on the other.[2]

Figure 2: Olympic sports hall today (Photo by Baris Wenzel)

2.2 Project participants

The realisation of these emblematic, light roofs required the cooperation of an interdisciplinary team of architects, engineers and university institutes. The architectural office Behnisch + Partner with Günter Behnisch, Fritz Auer and Jürgen Joedicke was already supported by the swiss engineer Heinz Isler during the competition phase, and in the course of the planning Frei Otto, as well as Fritz Leonhardt with his engineering office Leonhardt + Andrä with the project manager Jörg Schlaich joined the team. Frei Otto's Institute for Lightweight Structures (IL), the Institute for Model Statics under Robert K. Müller, the Institute for Applied Geodesy in Civil Engineering (IAGB) under Klaus Linkwitz and the Institute for Statics and Dynamics of Aerospace Engineering under John Argyris, all at the University of Stuttgart, were also involved in the planning.[3]

Figure 3: Some project participants during a discussion beside a model[4]

2.3 The sports hall

The roof of the sports hall spans an area of approximately 21,750 square metres and the principle of the supporting structure is similar to that of the stadium roof. It consists of five net surfaces lined up next to each other, whereby the central net has a continuous saddle-shaped curvature and the two fields on both sides represent turn-around surfaces. Two of the common nodes of the side nets were planned as low points in order to generate closed elements of the hall. The cable nets are held by two main masts, several smaller masts and two trussed cable-braced masts.[5] A mesh size of 75 x 75 centimetres was chosen for the nets in order to keep the number of nodes limited and at the same time to make the net accessible for scaffold-free assembly. The edge and ridge ropes were made from one or, if required, several ropes with a diameter of 8 centimetres. The net ropes were made of 19 thick wire strands to ensure the lowest possible susceptibility to corrosion. Various clamps were developed for the many different mesh angles and nodes, which were manufactured in the factory and could be rotatably adapted to the net on site. Larger steel elements, such as deflection saddles for guy ropes, were produced with the help of casting models, whereby moulds made of hard foam were carved for the first time instead of wooden models. The foam models did not have to be removed after being embedded in the sand mould, but were burnt out by the liquid steel during casting. The nets were covered with transparent sheets of acrylic glass and the joints between them were closed with a black neoprene profile.[6]

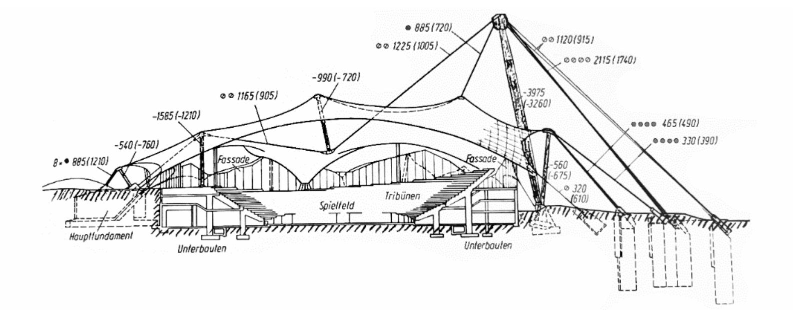

Figure 4: Construction principle of the sports hall[6]

2.4 Scepticism about the construction

Due to the enormous size and novelty of the proposed structure for the competition design, both the competition jury and international experts in the field of structural design were sceptical about the feasibility of the design. The Olympia Construction Company (Olympiabaugesellschaft), as the client, consulted several experts who expressed technical and economic concerns about the construction in terms of water drainage, snow loads, icing, wind loads, lighting, etc. These concerns were finally resolved as the planning progressed and became more detailed through the cooperation of the architects, Frei Otto and the engineering office Leonhardt + Andrä. Although the feasibility of the project continued to be discussed in public.[4]

2.5 The models of the sports hall

A decisive role in the progress of the planning played the physical models, which were built at the Institute for Lightweight Structures under the direction of Frei Otto. The geometrically complex shapes of the nets in prestressed state could not simply be represented by drawings, but had to be developed experimentally with the help of physical models. The production of prestressed cable net constructions in the model was also a challenge, as the geometry, the distribution of the prestressing forces, the construction of the net and the edges constantly influenced each other. For the first rough drafts of the shapes, models were built from polyester meshes and rods on a scale of 1:200, which served as the basis for initial static calculations and the models could be further optimised.[7]

The following more detailed measuring models were built on a scale of 1:125, the scale resulted from the size of the 3D measuring table at the Institute for Lightweight Structures with a size of approximately 150 x 180 centimetres. The measuring models were built in the following steps: First, the bending-resistant welded grid was produced. The mast base plates and bracing angles were attached to these at the specified coordinates. Then the masts and details were made and fixed at the designated points. The masts in the model had a maximum height of 56 centimetres and the installation of the trussed cable-braced masts with the associated curvature of the net was the particular difficulty in making this model. Then the edge wires with a thickness of 0.5 to 0.8 millimetres were installed and then the prefabricated net made of stainless, polished spring steel wire with a diameter of 0.2 millimetres was hung and soldered in place. The net had a mesh size of 24 millimetres and the nodes were represented by fine soldered copper wires, which were crimped to the net ropes. The wires had to be tensioned and released in several lengthy passes to achieve the required state of tension.[8]

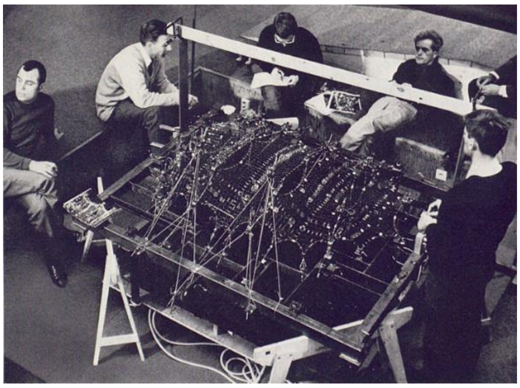

Figure 5: Measurement model of the sports hall at a scale of 1:125 on the measuring table at the IL[9]

2.6 Model tests

The model frame for the model of the sports hall was approximately 160 x 250 centimetres and the model thus had to be moved during the measurement on the measuring table. On the other hand, the model was measured photogrammetrically at the Institute for Applied Geodesy in Civil Engineering (IAGB) under the direction of Klaus Linkwitz. The deformations during the loading tests were also measured manually at the measuring table, as well as with photographic double exposures or multimedia short-time tests by taking snapshots of deformation states and measuring devices. For the mechanical measurements of forces, ring force gauges, measuring brackets and dial gauges were used, which could measure actual absolute forces. Force changes in the edge wires were determined at the Institute for Model Statics under the direction of Robert K. Müller using strain gauges. The different loads were simulated with the help of weights, which were hung on hooks and chains in the net nodes. The weights were supported on a base plate, which could be raised or lowered completely or partially with hoses made of car tyres. The measurement results were then used in the further static calculations by the engineers from Leonhardt + Andrä.[8]

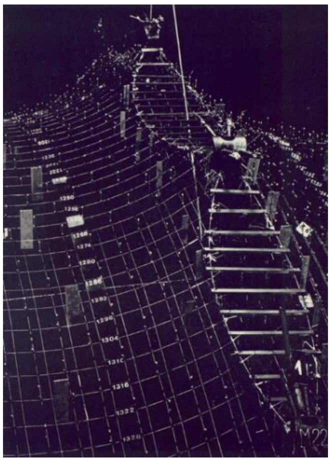

Figure 6: Detail of the measurement model of the sports hall at a scale of 1:125[9]

2.7 Determination of the cable net patterns

The patterns of the cable nets should also be created by photogrammetric recordings of the measuring model, but the measuring model, especially the uniformity of the mesh, had become too inaccurate as a result of the tests carried out on it. Therefore, a new model with geometric similarity to the real structure had to be built to determine the patterns. The highest value was placed on the precision of the mesh and detailing of the nodes, but the pattern model for the sports hall was still too inaccurate to generate the patterns geometrically. This problem was solved with the involvement of the Institute for Statics and Dynamics of Aerospace Engineering under the direction of John Argyris. Using the finite element method, the patterns could be calculated electronically on the basis of the photogrammetric exposures.[8]

The model of the sports hall that should have been used to determine the patterns is one of the few surviving models from this period of using physical models in civil engineering. Today, the model can be found in the visitors' centre of the Olympic Park in Munich.

3 DIGITAL TWIN

3.1 Definition

Digital twins are digital representations of things from the real world. In Industry 4.0, the digital twin is one of the main concepts that should drive the digitization of industrial production. While the term is used more and more in the aerospace and automotive industries, there are still few known applications in the architecture, engineering and construction sector.[10] The industries that are more dependent on industrial production can offer the construction industry an important orientation in dealing with digital planning and management, since comprehensive networking of data sources and the coupling of simulation models are also becoming more and more indispensable in the building process.

3.2 Usage and benefits

3.2.1 Sociocultural benefits

A central collection, digitization and publication of all related data of that time threatened contemporary witnesses can be the basis for getting more and more young people enthusiastic about research and innovation in the construction industry. In this way, on the one hand, the results should be verifiable and on the other hand, the individual model as a document relating to the history of building technology, as a store of knowledge for further research and as an instrument for targeted, qualified promotion of young talent - also with regard to a sustainable, research-friendly future viability of the Civil engineering.[1] Especially, the pandemic situation has shown the value of a digital collection which is easily available to a large audience in full scope.

3.2.2 Technical benefits

Like their material brother, they are knowledge stores of their own value, carriers of information about a lost engineering practice of producing findings and their communication and transfer into building practice. Using the method of selective creation and use of digital comparison models for this outstanding object, the results at that time are assessed as necessary with the then and with the current level of knowledge and effort, authenticity, clarity, measurement method, test procedure, documentation of tests or accuracy.[1] Furthermore, changed framework conditions caused by climate change such as greater amounts of precipitation and increased snow loads or wind effects can be simulated and evaluated.

3.3 Reverse engineering

3.3.1 Methods

The difficulty in collecting the data for the reverse engineering were the filigree wires, some of which have a cross section of only 0.2 mm. In order to be able to get the knot vertices of the wires several destruction free measure methods were tested on test model of a representative portion of the original model containing the most difficult areas.

3.3.2 Structured Light 3D-Scan

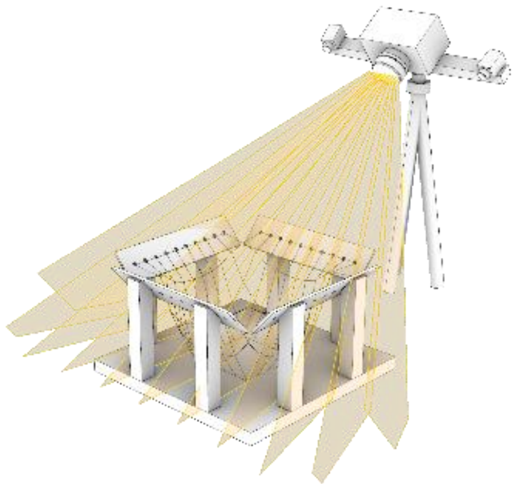

Figure 7: Structured Light 3D-Scan diagram

Functionality: A 3D model of a face is computed by projecting a simple stripe pattern onto the object. The depth information is then calculated by considering the distortion of the stripes in the object caused by its shape. To measure the degree of distortion the projected stripes are compared with the detected stripes in order to find corresponding stripes respective to find corresponding pixels per vertical scan line. The depth is evaluated for all correspondences with respect to the focal points of the camera.[11] This leads to a cloud of 3D points.

Result: With this method, the thin wires were not depicted in the point cloud.

3.3.3 3D-Laserscan

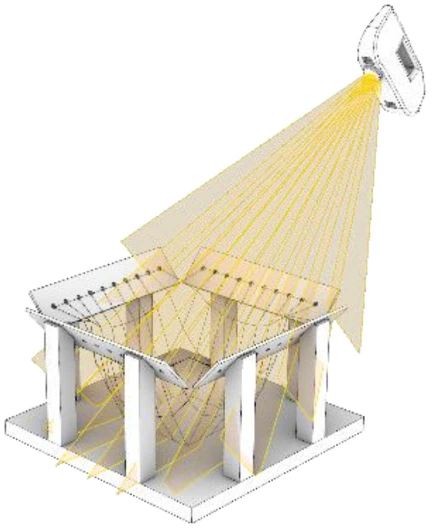

Figure 8: 3D Laser-Scan diagram

Functionality: The scanner emits a laser beam, which is then reflected back by the surroundings and picked up by the receiving optics. The beam is deflected by a deflecting mirror that is set in rotation. This process takes place several hundred thousand times a second. The laser light received again by the scanner is then evaluated accordingly.[12]

Result: With this method, the thin wires were only depicted in outline in a very blurry point cloud, which was not nearly accurate enough to reverse engineer the filigree wires within a reasonable tolerance.

3.3.4 Photogrammetry

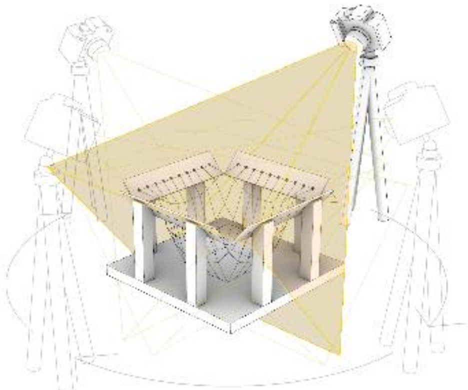

Figure 9: Photogrammetry diagram

Functionality: For the photogrammetric method, images of an object are first recorded from various angles. Every externally visible point must be clearly visible in at least two photos. In the photogrammetric evaluation of images, the imaging geometry must be restored at the time of recording. This restoration takes place according to the laws of central projection in compliance with the condition of planarity. By using at least two homologous (corresponding) image points from two different recording positions (stereo image pair), if the mutual position (relative orientation) is known, the two rays can be brought to the intersection and thus each object point can be calculated three-dimensionally.[13]

Result: This method is the most time-consuming, as it is manual, but also leaded to the best results. Instead of getting a generated point cloud, every relevant point(intersection vertices of the cables, highpoints, anchorpoints) was extracted manually.

3.3.4 Conclusion

Interestingly, in the end, photogrammetry turned out to be the most accurate method. So the digital twin was generated by using the same method that was used 50 years ago to measure the deformations on the original model.

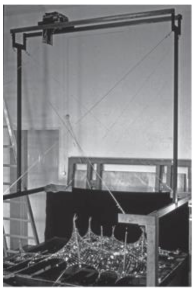

Figure 10: Photogrammetry used for the Montréal pavilion[14]

Figure 11: Photogrammetry used for the Olympiapark model

3.4 3D-Modelling

3.4.1 Data Processing Scheme

Due to the size and complexity of the model, for this case study it was decided to model the half and mirror it. The original model and the original building, however, are not mirror-symmetrical.

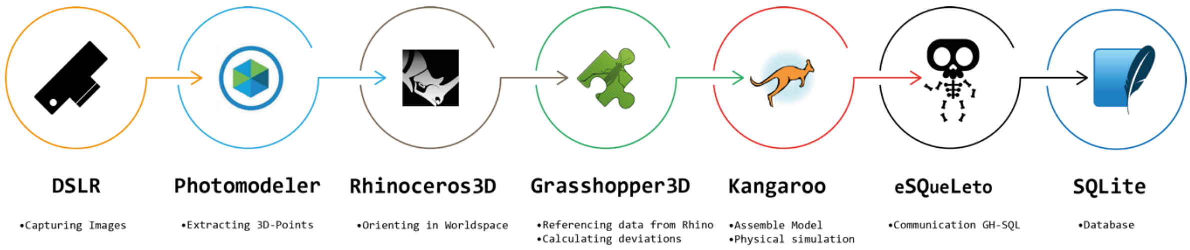

Figure 12: Data Processing Scheme

The process begins by taking photographs of the model with a digital single-lens reflex camera (Pentax K1 with 31mm lens). The photos serve as the basis for the extraction of relevant 3D points with the photogrammetry software Photomodeler. In order to make this possible, the recorded images are referenced in a first step using target points and an overlap of the images is calculated. Then Rhinoceros3d is used to scale the geometry and align the extracted points in a global coordinate system. To automate the creation of masts, foundations and the mesh which describes the cable net Grasshopper3D was used. This graphical algorithm editor is tightly integrated with Rhino's 3D modelling tools and agilizes the process tremendously. A particle-based live physics engine (Kangaroo2) that lives in Grasshopper was used to simulate the cablenet under the most realistic conditions possible. In order to be able to manage the big amount of data it was necessary to transfer the generated information in a SQLite database. The eSQueLeto Plug-In was designed and written in C# to enable a live connection between Grasshopper and the SQLite Databasefile.

3.4.2 Deviation Analysis

To check the accuracy of the photogrammetry 7 target points were projected onto their average plane and the distance measured. The result has shown that the method is very accurate, with an average deviation of 0.4 mm. The outlier was with 0.89 still under one millimetre.

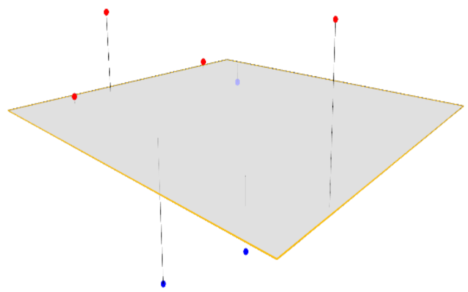

Figure 13: Diagram of target point deviation

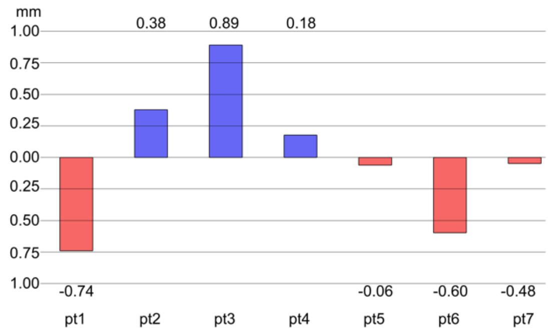

Figure 14: Deviation Analysis of the target points

3.4.3 Cable net modelling

The base mesh was created manually using the high and low points extracted from the photogrammetry as anchor points. The topology of the base mesh is extremely important for the subsequent processing. In a next step, the mesh was subdivided using a recursive constant quad split algorithm. In a last step it was relaxed to simulate the cable net structure in tension.

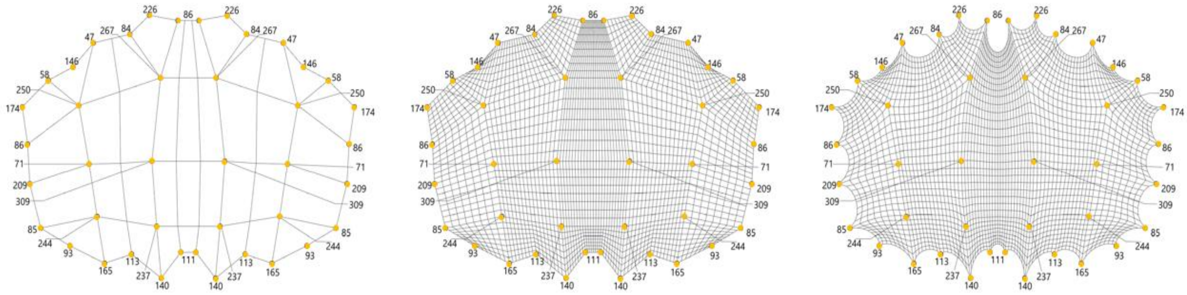

Figure 15: Base mesh layout; Subdivided mesh; relaxed mesh. The points show the anchors points with their respective Z-value.

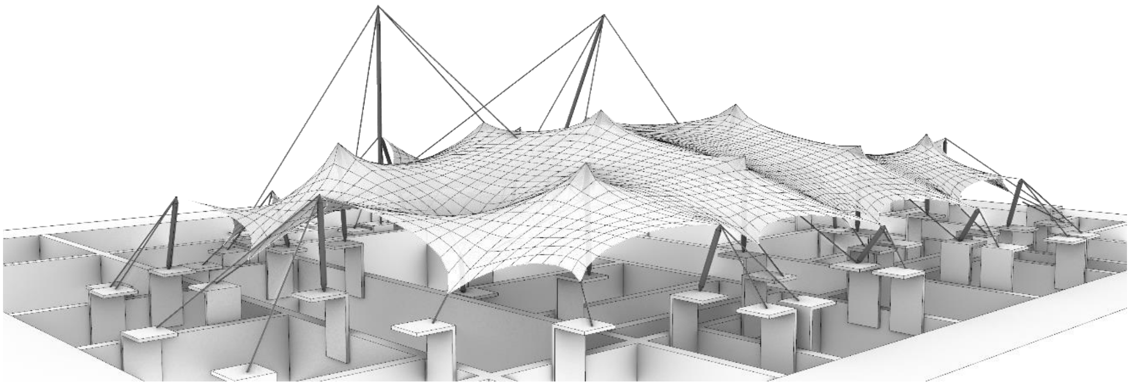

Figure 16: Representation of the digital twin

3.5 Database

The final model consists of a mesh with an area of 1.42m^2. It is described by 2560 faces, 5256 edges and 2697 vertices and spans from 24 masts, held by 56 cables.
These figures give an idea that without a corresponding data management any processing and use would be difficult to accomplish. The database makes it easy to categorize, manage and catalogize the data.

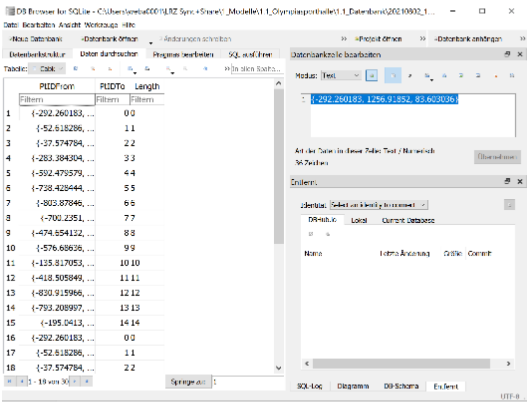

Figure 17: SQLite database in DB Browser

4 Conclusions

Similar to the construction of the building treated in the paper testing on smaller models was used to develop the methodology and check the realizability. So, the successful recording of the original objects at their location could be tested and guaranteed.
Thus, important step was achieved for the record of one of the last witnesses of construction history. The data contained in the digital twin now can serve as the basis for cataloguing and categorizing the objects with an easy accessibility for interested people all over the world.
Further it will serve for the location of the damage, providing a valuable basis for restorative processes. The possibilities for future usage are immense: besides structural calculations for mutable factors like caused by climate change, as teaching material or to explore in exhibitions with virtual reality among others.

5 REFERENCES

[1] Putz, Möller, Weber, *“Last Witnesses” – physical models in civil engineering – scientific meaning and Conservation*
[2] Anette Bögle, Peter Cachola Schmal and Ingeborg Flagge (Ed.), *Light Structures – Jörg Schlaich Rudolf Bergmann*, Prestel, 2003.
[3] Benjamin Schmid and Christiane Weber, The experiments on measurement models for the Munich Olympic site. *History of Construction Culture* (2021) 1:625-631.
[4] Winfried Nerdinger (Ed.), *Frei Otto Das Gesamtwerk – Leicht Bauen Natürlich Gestalten*, Birkhäuser, 2005.
[5] Fritz Leonhardt, *Baumeister in einer umwälzenden Zeit*, Deutsche Verlags-Anstalt, 1984
[6] Jörg Schlaich et al, Das Olympiadach in München. *IABSE Kongressbericht* (1972) 9:365-376.
[7] Jörg Schlaich et al, Das Olympiadach in München. *Das Werk: Architektur und Kunst* (1970) 11:365-376.
[8] Frei Otto (Ed.), *Netze in Natur und Technik*, Krämer, 1975.
[9] Lisbeth Sachs, Die Dächer von Frei Otto. *IABSE Kongressbericht* (1972) 9:734-741.
[10] https://gi.de/informatiklexikon/digitaler-zwilling/
[11] Philipp Fechteler, Peter Eisert and Jürgen Rurainsky, *Fast and High resolution 3d Face Scanning,* International Conference on Image Processing (ICIP 2007)
[12] Clive Boardman, *3D Laser Scanning for Heritage Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture*
[13] Thomas Lumann, *Close Range Photogrammetry Principles, techniques and applications*
[14] Bill Addis, *Physical Models, Their historical and current use in civil and building engineering design*, Christiane Weber 14 Physical modelling at the University of Stuttgart