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Special features of design and execution of MERO type spatial structures

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Professional paper

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Special features of design and execution of MERO type spatial structures

This paper presents a specific type of steel spatial structural systems whose bolted connections are realised in the MERO system. The features of the concept of the system itself are given and its components, design principles and peculiarities, transport method and specific assembly methods are described in detail. Finally, the descriptive part of the work is accompanied by examples of constructed buildings, for which the particularities of design and execution are given. The advantages of the MERO type solutions described are emphasised in the conclusion of the paper.

Key words:
steel, design, MERO type spatial systems, lightweight, simple transportation, fast assembly

Stručni rad

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Specifičnosti projektiranja i izvedbe čeličnih prostornih konstrukcija tipa MERO

U ovome radu predstavljen je specifičan tip čeličnih prostornih konstrukcijskih sustava čiji su vijčani spojevi izvedeni u sustavu tipa MERO. Dane su značajke koncepta samog sustava te su detaljno opisane njegove komponente, principi i specifičnosti projektiranja, način transporta i specifične metode montaže. Naposljetku, deskriptivni dio rada popraćen je primjerima izvedenih građevina za koje su navedene specifičnosti projektiranja i izvedbe. Prednosti opisanih rješenja tipa MERO istaknute su u zaključku rada.

Ključne riječi:
čelik, projektiranje, prostorni sustav tipa MERO, mala težina, jednostavan transport, brza montaža

1. Introduction

The architectural design creativity that we see in many modern buildings was largely made possible by the development of spatial structures that enabled the construction of many geometrically demanding structures. Figure 1. shows an example of such an irregular and uneven spatial structure of the building envelope. The obvious task is to ensure the connection of many structural members in a large number of nodes. Each node has multiple members connected to it and the members are spatially arranged, resulting in a complex force transmission mechanism [1] and complicating the construction itself [2]. Therefore, to satisfy the need for an efficient and reliable connection system, many such systems have been developed, about 250 according to one source [1]. Some of the more notable ones are UNISTRUT, NODUS, Space deck, Triodetic and, after all, MERO.

Figure 1. Cultural center in Baku, Azerbaijan [3]

The MERO system is a specific solution for the design of spatial trusses in which the tubular members are bolted to spherical node with threaded holes. Originally, it was used for flat, two-layer trusses where a large number of equal members and nodes could be achieved, which was suitable for serial production. Today, due to the irregular geometry, the design approach tends to focus on standardised cladding techniques where the tendency is towards similar cladding surfaces [4]. The adaptability to all geometries makes this system suitable for many different types of structures such as markets, sports halls, airports, canopies, industrial halls and much more.
The advantage of this system for force transmission is that the axis of each member passes through the centre of the node, which avoids eccentricities and the resulting bending moments [5]. In addition, the size of the individual tubular member is adapted to the range of the force they must carry, which raises the issue of weight optimisation. On the other hand, numerous bolted connections reduce the stiffness of the nodes, which leads to greater deflections and must be considered [6].

MERO+ system, was developed. Its main feature is the replacement of part or all the top chord with standard hot-rolled profiles, which act as purlins and eliminate the need for an additional secondary structure supporting the cladding [7].
To reduce the height of the structure even further, a modified version of the MERO system, the [7].
The design of these structures is usually related to the availability of local production facilities for MERO components. The closure of these plants has reduced the frequency of design of this type of structure. The basic features and principles of the MERO system, which have been neglected in recent years, are presented in this article.
The concept of the MERO system is explained, and a brief description of the design process is given. The article concludes with some design methods and real examples of finished spatial structures.

2. MERO system concept

2.1. General

The core of the MERO system technology lies in the steel parts that form the nodes of the spatial truss. The parts include the tube, cone, bolt, dowel pin, sleeve and sphere. The abbreviation "MERO" itself stands for "Mengeringhausen Rohrbauweise" (Mengeringhausen's tubular structures) [8]. The basic structural member of the MERO truss is a steel tube with a steel cone and a sleeve on each side and a bolt with a dowel pin inside. The cones are welded to the tubes, which are then hot-dip galvanised. After galvanising, the bolt is inserted into the cone through a mounting hole in the tube and the sleeve is connected to the bolt with dowel pin [8]. The entire assembly is then connected to a spherical node by twisting the sleeve with a spanner. Member scheme is shown in Figure 2. where d_m - mounting hole diameter, s - wall thickness, h_c - sleeve height, h_k - cone height and d_k - lower cone base diameter.

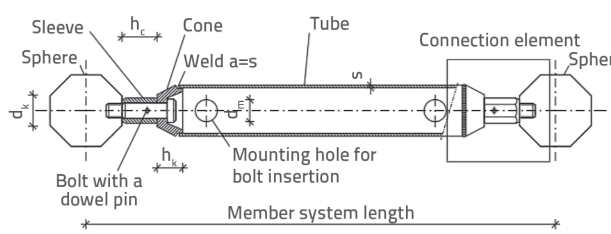

Figure 2. Elementary MERO member and its components

The MERO system is not standardised. Instead, its rules are governed by the technical approval (hereinafter *T.A.*) [9] which specifies the particularities of design, calculation, quality control and construction. The typical node detail, in which all components are interconnected, is shown in Figure 3. The individual components are briefly described in the following subsections.

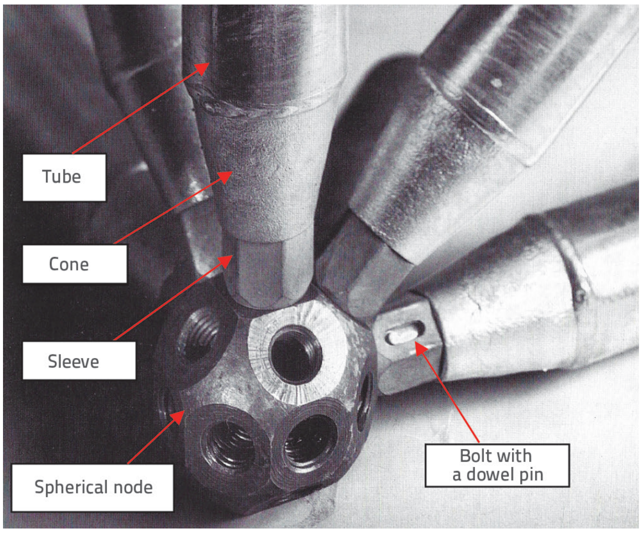

Figure 3. MERO system components - typical node [8]

2.2. Tube with cone ends

According to T.A. [9], tubes for MERO structures are made of S235 and S355 steel. Tube slenderness is limited to 150. According to [10], an exception is only permitted for tube diameters of 42.4 mm (max. slender. 200), 60.3 mm (max. slender. 185) and 76.1 mm (max. slender. 170). The requirements for the toughness of the tubes are not strictly defined by T.A. When welding the cones to the tube, their axes must coincide with the tube axis. The steel grade and toughness requirement for the cones is S235J2 or S355J2 [9]. They form an inseparable whole with the tubes.

Figure 4. shows the possible types of welds between cone and tube. If the tube wall thickness is 5.6 mm or less, a fillet weld is used. Butt welds and HV welds are used for thicker tube walls [10].

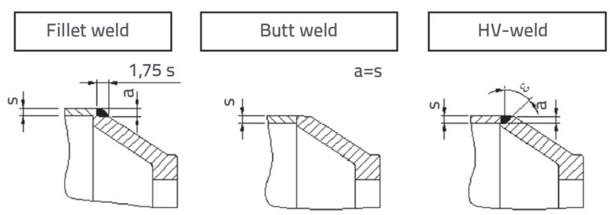

Figure 4. Cone-tube weld types [9]

Tube with cone ends must be suitably protected against corrosion. The usual method is hot-dip galvanising, except for decorative MERO elements, which are usually smaller tubes where anodising is used [8]. Hot-dip galvanising is suitable in this case, as the inside of the tube is exposed to a potential risk of corrosion due to the fixing holes for the bolts. An exclusively external coating is therefore out of the question.

2.3. Sleeve

The sleeve is a component that encloses the bolt and serves as a mediating element that supports the bolting of the bolt in the node. It is made of S355 steel and is also hot-dip galvanised against corrosion [9]. Figure 5. shows a hexagonal sleeve with slotted hole and round hole. The type with a slotted hole is intended for bolts up to M20 [10]. The smaller sleeve base is rounded at the corners and orientated towards the sphere. The spanner width with which the sleeve is turned must be 1.2 times the bolt diameter that fits into the sleevei [9].

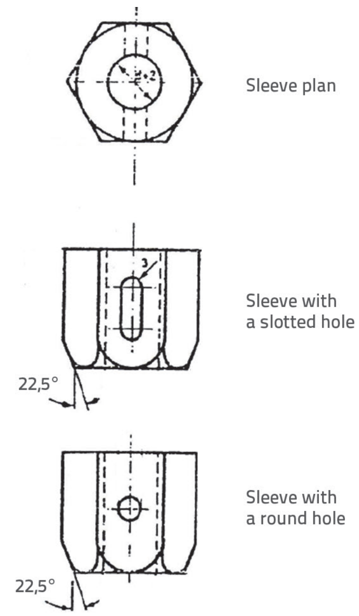

Figure 5. Hexagonal sleeve types [10]

2.4. Bolt and dowel pin

The bolt is the main connection mechanism in nodes for this type of structure. A typical bolt scheme is shown in Figure 6., where d_s - dowel pin hole diameter, d_{bk} - bolt head diameter, d - bolt body diameter and M - thread diameter. All bolt dimensions are defined in T.A. [9].

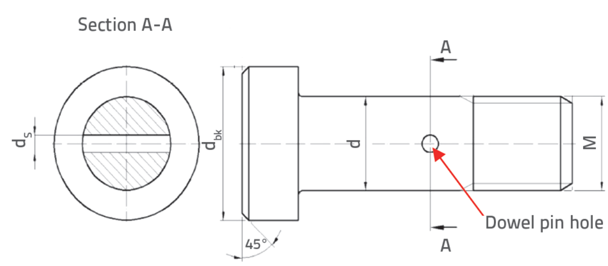

Figure 6. Typical bolt scheme [9]

There is a hole in the bolt body through which the dowel pin is inserted. The dowel pin is a small cylindrical wedge that connects the bolt to the sleeve. Its diameter ranges from 4 mm to 8.1 mm, depending on the bolt diameter, and its length corresponds to the diameter of the sleeve. The minimum permissible bolt size is M12. The maximum bolt size is limited to M90. T.A. also prescribes a rule regarding bolt size gradation within the structure. It states that the nominal diameter of the bolt thread must be smaller than the core diameter of the next bolt. Due to this rule, the following bolt combinations cannot be used: 24 + 27; 27 + 30; 30 + 33; 33 + 36; 48 + 52 and 52 + 56 [9]. For most tension members, the bolt is the weakest component.

2.5. Sphere

The spheres are nodal elements of the MERO system in which the tubular members are interconnected. According to [9], the spheres are usually made of hot-pressed C45 quenched and tempered steel (non-alloy carbon steel), the composition of which is specified in the standard [11], and then either normalised or tempered. If the sphere is to be welded, the steel S355J2 is the most suitable due to its better weldability. On the other hand, bolted connections with S355 steel are somewhat weaker than with C45 steel. The use of such an alternative material would be necessary, for example, in the construction of a support sphere which requires the welding of additional steel reinforcements.
In addition, certain flattening of the sphere surface in the area of the bolt holes must be carried out in order to achieve complete contact between the sleeve and the sphere. The threads inside the sphere must be metric in accordance with the standards [12, 13] and their depth is specified in T.A. [9], as is the screw-in depth of the bolt. A sphere can have 18 members connected to it, with a maximum of 8 of them in the same plane [9]. The sphere's size varies between 50 and 500 mm in diameter or between 0.5 and 500 kg in relation to its mass. It is also possible to provide additional holes in the sphere, if necessary, e.g. additional holes in the upper chord spheres for the supports of the secondary structure. On the other hand, additional holes can be drilled through the entire sphere if external connections are required above and below the sphere, e.g. if various equipment needs to be suspended below the bottom chord sphere and a catwalk for structural inspection is planned above the bottom chord sphere and its supports are to be mounted in the spheres.

3. Special features of the design

Spatial truss structures with MERO components conceptually follow a trend towards the repetition of regular spatial modules in their composition. This trend enables more uniform member lengths which in turn makes the serial production of truss members more efficient. The basic bodies that form the spatial modules are the tetrahedron, the eighth of the octahedron and the quarter of the octahedron, Figure 7, according to [8] (same colour = same length).

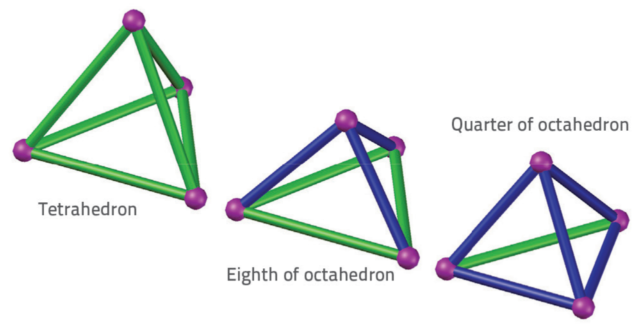

Figure 7. Fundamental spatial modules [8]

In addition to the conceptually acquired uniform member lengths, there is also a need for relative uniformity in member cross-sections, i.e., member types. Since rational serial production is one of the basic principles of the MERO system, a catalogue of typical tubular members with defined components was developed to cover a wide range of load ranges. Due to the size of the catalogue, only a small section is shown in Table 1. The previously mentioned member type refers to the category "Type" from Table 1. and represents a specific combination of components that are summarised under a unique trade name, e.g. type D3. The bolts labelled "L" (marked with * in Table 1) are slightly longer than the other bolts as they have a thicker cone, which is typical for this member type.
Load capacities from the table above represent the design values of resistance. Partial coefficients for every respective characteristic value of resistance depend on the nature of

Table 1. Typical MERO system members (excerpt from catalogue [14])

					Load capacity [kN]	
Type	**Tube**	**Steel**	**Bolt**	**Sleeve**	**Tension**	**Compression**
D3	60.3 x 2.9	S235	M20 5.6	30/22	**49.2**	**82.8**
F3	76.1 x 2.9	S235	M20 8.8	30/22	**104.9**	**105.6**
G3	88.9 x 3.2	S235	M20 8.8	30/22	**104.9**	**116.0**
G5	88.9 x 4.5	S235	M20 10.9	36/22	**131.1**	**189.0**
H3	108.0 x 3.6	S355	M20L* 8.8	41/22	**104.9**	**265.0**
H3A	108.0 x 3.6	S355	M27 10.9	41/29	**265.0**	**234.2**
K3	127.0 x 4.0	S355	M20L* 8.8	41/22	**104.9**	**327.9**

resistance itself. The resistance of MERO member can be understood through the analogy of a chain and its weakest link, where the 'links' are tube, cone, sleeve and bolt. The lowest resistance value among these segments represents the load capacity of the member as a whole. Thus, if, e.g., the tensile strength of a bolt is the lowest resistance among others, the partial coefficient g_{M2} for bolted connections is applied.

The idea of the approach with a defined catalogue like this is to form a member type list from which a structure will be made before the actual structural design. The member type list usually consists of 10 to 20 member types, depending on the range of the internal forces. In this way, a relatively wide range of internal forces can be covered and the structure can be well optimised by using a suitable member type in each part of the structure. Using a larger catalogue can lead to a more expensive structure as a large number of member types have to be machined individually. A catalogue that is too small can also lead to an expensive design, as the range of internal forces cannot be adequately covered and the design is not optimised. The possibility of compiling such a type of catalogue yourself can lead to an additional exchange of catalogue types if the calculation reveals that one or more types are unused or the range of internal forces is not well covered.

It's important to note that all connections in the truss are considered hinged and all tubular members are designed for axial tension and/or compression forces [9]. An exception is made for all members with an inclination of less than 30°, which are additionally loaded with a vertical load of 1.0 kN (characteristic value) at the centre of their span [9] to simulate a fitter standing on them. All other loads must be concentrated in the nodal points of the spatial truss. As a result, the design concept can be summarised in just a few steps:

- Selection of the member cross-section
- Structural analysis – calculation of internal forces and deflections
- Member design
- Optimum cross-section selection
- Evaluation of the results

It's an iterative process where the 1st step is repeated after the 4th, which is a single iteration of the design. After each iteration, a percentage of changed members is noted. This process can be terminated when a reasonably small percentage of modified members is reached, i.e. when a convergence of member cross-sections has been achieved. In this case, the 5th step can begin, in which the results are evaluated. The suitability of the selected member type list is checked and the necessary replacements can be made if required.

Figure 8. shows an example of the histogram of member utilisation of an advantageously designed structure. It can be seen that most of the members have a high degree of utilisation and fewer and fewer members achieve a low degree of utilisation. This is the result of good alignment between the catalogue and the structure. Only when all the members have been designed, we can start to determine the size of the spheres in the nodes. Like the tubular members, the spheres are also selected from a commercially available sphere catalogue, but their size depends only on the geometric conditions in the nodes. The neighbouring members must not collide with each other and there must be no contact between the bolts inside the sphere. This can be achieved by using a suitable sphere diameter.

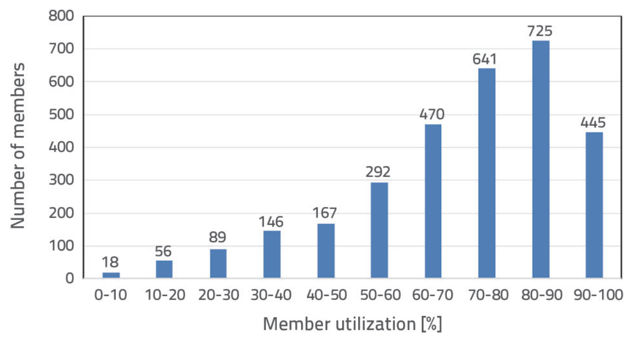

Figure 8. Member utilization histogram of a fully designed structure [7]

Due to the numerous bolted connections, there is a certain amount of flexibility of the nodes, which leads to higher deflections than those calculated in the linear analysis. Previous structural tests on finished structures and virtual analyses on models have shown that a good approximation to flexibility of MERO-type structures can be achieved by reducing the modulus of elasticity of the steel or inducing an initial deflection [6]. The initial deflection can be estimated to be 10 % of the total deflection calculated from the load combination that gives the largest deflection and the modulus of elasticity can be reduced to 85 % of its value [6]. If these approximations still lead to dubious results, a second-order analysis must be performed.

4. Special features of the assembly process

The transport of MERO structures is favoured by two facts. Firstly, MERO structures are generally very light, which can reduce the cost of transport itself. Secondly, MERO structures are assembled on site and can be delivered there in their basic components. The components can be packed in crates, on pallets or in containers for more compact and efficient delivery to the construction site. Figure 9. shows the transported MERO elements, ready for assembly.

The assembly methods for MERO structures can be roughly categorised into 4 types.

The first method is free cantilevered assembly, where the structure is built up step by step from the foundations to its final position. The members are connected one by one or in a smaller assembly. With this type of assembly, entire structures can be assembled using only trained fitters, a crane and nothing else. For larger structures, the fitters form several groups, usually consisting of 3 workers [8]. Additional workers assemble the parts of the structure on the ground, which are then lifted by crane to the position, where they are finally connected by the assembly groups. One such method is shown in Figure 10.

Figure 9. MERO members temporarily stored on site

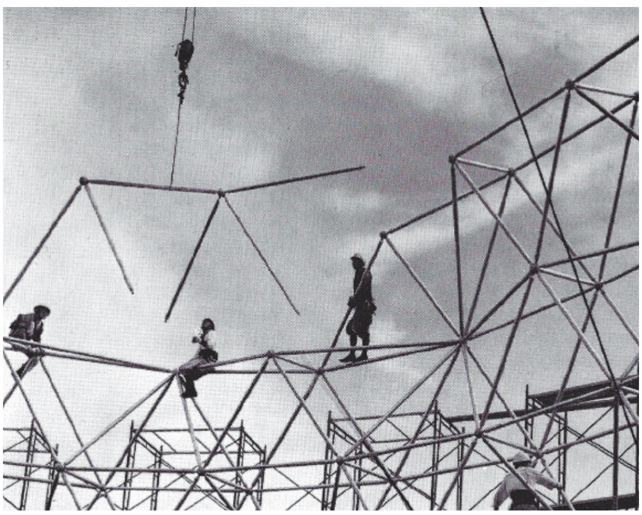

Figure 10. Free cantilevered assembly method [8]

and then lifted into place using a crane or similar machine. With this method, many more people can work on the assembly at the same time, and the supervision of assembled parts is easier, so that the assembly can be completed more quickly and therefore earlier. An example can be seen in Figure 11.

The third method is the segmental assembly of statically independent large-area roofs. Figure 12. shows the sequence of work steps for this method. The practicality of this method lies in the possibility of carrying out the construction work under the finished roof, which protects the workers from unfavourable weather conditions [8]. In the second method, the structure is assembled on the ground [8].

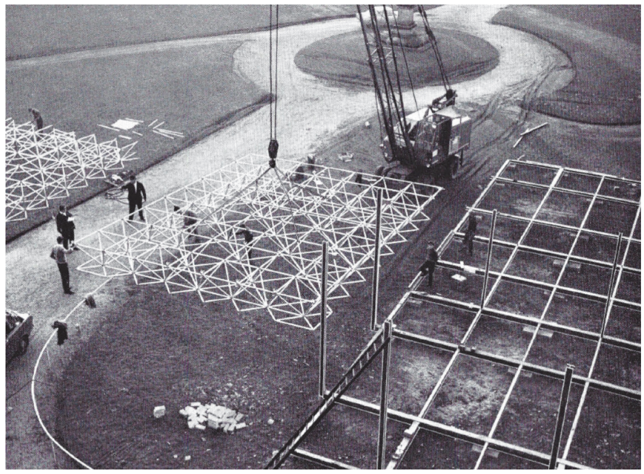

Figure 11. Erection of an assembled structure with crane [8]

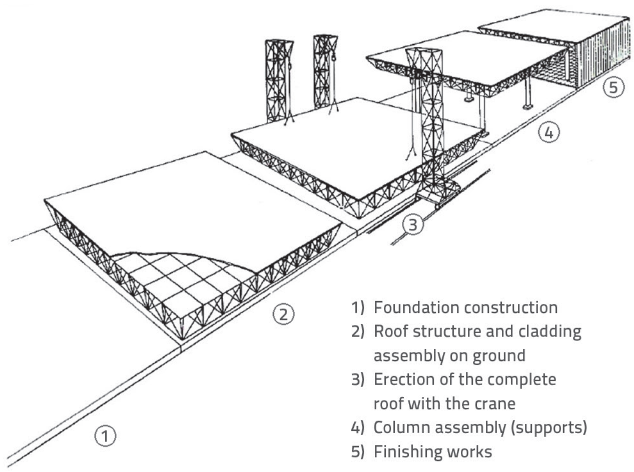

Figure 12. Segmental method's order of operations [8]

The fourth method involves assembling the structure on the ground and placing it on already built supports located on the outline of the structure. This method, when applicable, is suitable for sports structures that don't have supports in the main span [8]. The erection of a structure using the fourth method is shown in Figure 13.

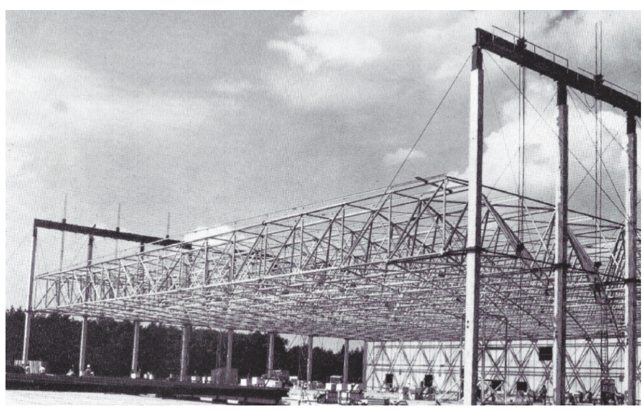

Figure 13. Erection of a fully assembled structure on supports [8]

5. Examples of carried out MERO-type structures

5.1. Franjo Tuđman International Airport Zagreb

The new passenger terminal at Zagreb International Airport consists of the main building, two side extensions (one on each side of the main building) and 8 passenger boarding bridges extending towards the runway, Figs. 14. and 15. Main designers were architects Branko Kincl and Velimir Neidhardt while the main structural designer was Jure Radić. The contractor for the steel part of the structure was Zagreb Montaža and the main contractor was Bouygues International, a french company. The roof over the main building and the annexes is designed as a space frame made of components from the Željezara Sisak Space System, which is the conceptual successor to the MERO system in this region. Due to its pronounced undulating appearance, the roof has many members of different lengths and is a true example of the geometric variety and slenderness that can be achieved with such spatial trusses. It consists of a total of 25477 tubular members, 6119 spheres (nodes) and 102 columns. The tube diameters vary between 88.9 mm and 219.1 mm. The tubes and spheres are manufactured in Croatia and each member has a unique ID number. This is very important when the geometry is very irregular and the positioning accuracy of the individual members is crucial. The roof has a total area of 55000 m^2 and weighs 1400 tonnes, i.e. it has a surface weight of 25.5 kg/m^2, which makes it an exceptionally light structure. Assembly began in March 2015 and took around 5 months.

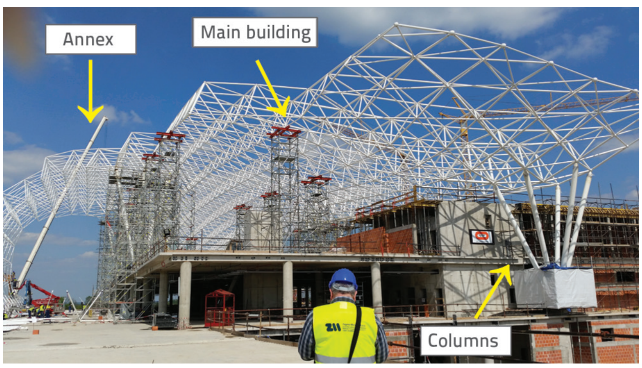

Figure 14. Characteristic new terminal segments in the construction phase

Figure 15. New terminal shortly before completion [15]

5.2. Dražen Petrović Basketball Centre

The Dražen Petrović Basketball Centre in Zagreb is a multifunctional sports hall whose roof consists of a Željezara Sisak Space System spatial truss. Main designers of the complex were architects Hržić, Šerbetić and Piteša, and the main structural designer was Milutin Anđelić. The main contractor was a company named Vladimir Gortan, while the steel roof was realised by Željezara Sisak. It has an oval shape with a shorter span of 60 metres and a longer span of 74 metres. The structural height on the supports is 2.95 m and 1.8 m in the centre of the span. The ground plan and the characteristic section of the structure can be seen in Figure 16. The greater height at the supports enables the accommodation of equipment in the structure. Construction of the sports hall and the neighbouring office tower began in February 1986 and the sports hall was opened in June 1987. The assembly of the steel structure took only 2 months. Short construction times and a tight construction site with little space for machinery meant that this system was chosen for the roof structure due to its flexible assembly options and the wide range of geometries it can fulfil.

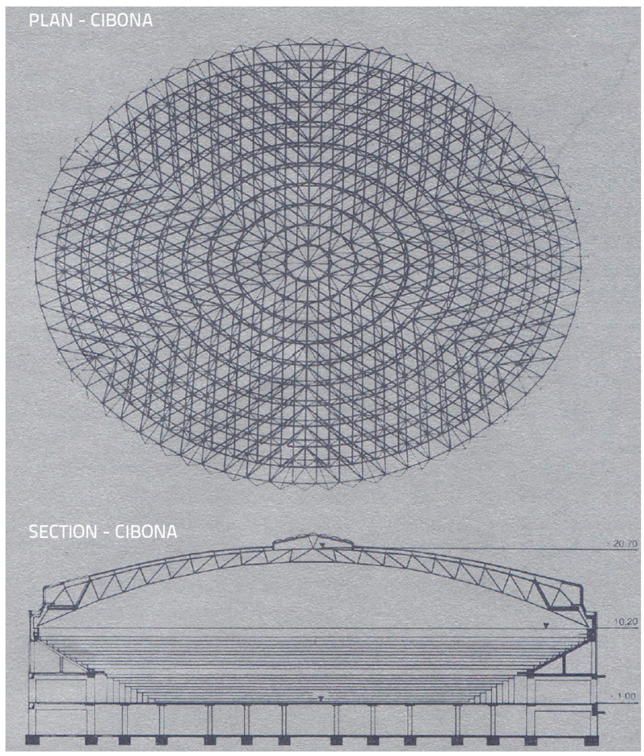

Figure 16. Sports hall's ground plan and the characteristic section [16]

The uniqueness of this structure lies precisely in its oval shape, which represented a very difficult and complex task, not only for the structural calculation but also for the adaptation of the grid. Despite the difficulties in design and construction, a very acceptable solution was found. The structure consists of a total of 3210 tubular members, 793 spheres (nodes) and 66 supports. The tube sizes vary from 60.3 mm to 219.1 mm in diameter. The total weight of the structure is 135 tonnes, which corresponds to 38.7 kg/m^2 according to the shape and span mentioned. The interior of the sports hall with the roof installed can be seen in Figure 17.

Figure 17. Sports hall's interior [16]

5.3. Poljud Split City Stadium

The Poljud Stadium is the most important stadium in the city of Split and the home ground of the football club HNK Hajduk Split, Figure 18. It was built in 1979 to host the 8th Mediterranean Games. The stadium owes its architecture to Boris Magaš, while the main structural designer was Božidar Jelić from company Lavčević. The main contractor was Hidroelektra, while the steel roof was assembled by Dalmastroj and Goša through instructions from MERO company. Construction of the stadium began in 1978 and took just 20 months, of which 3.5 months were needed to assemble the steel roof over the seats. The roof consists of two mirror-symmetrical MERO spatial trusses in the form of cylindrical shells, which cover the eastern and western seating areas of the stadium.

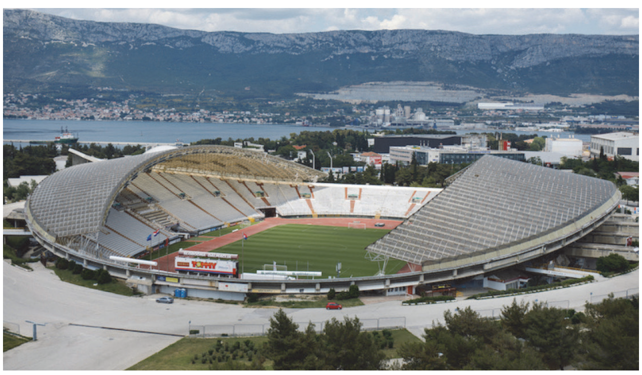

Figure 18. Poljud Split City Stadium [17]

The span of the inner arch is 215 metres, the ground plan width is 41 metres and structural height is 2.3 metres. In total, the roof consists of 12460 tubular members, 3460 spheres (nodes) and 28 supports and 28 MERO member types. The total area of the roof is almost 20,000 m^2, and with a weight of 688 tonnes, the weight per unit area of the structure is 34.4 kg/m2. The measurement of the initial deflections when the structure was gradually relieved of the auxiliary supports revealed deflections that were up to twice as large as in the first-order analysis [18]. Further tests and computer analyses using the second-order theory showed that the cause of the larger deflections was the flexibility of the nodes, which hadn't previously been taken into account. This example served as a guideline for future designs of structures like this in terms of taking node flexibility into account. Figure 19. shows the stadium roof in the phase of construction. The first supporting tower made of heavy scaffolding was positioned in the middle and the initial roof segment assembled on the ground was put on top of it. By applying the free cantilevered assembly method, the segment was firstly connected to the support on the edge after which the rest of the roof was gradually assembled on each side from there with the help of supporting towers.

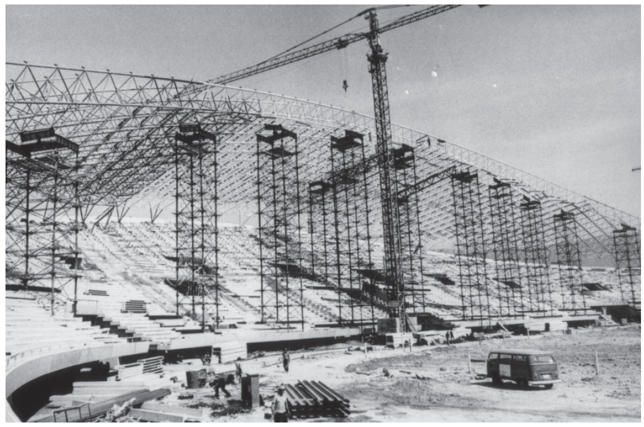

Figure 19. Poljud Stadium roof – construction phase [19], author HNK Hajduk

5.4. Otoka Sarajevo Olympic Pool

The Otoka Olympic Pool is a covered swimming pool in the city of Sarajevo. It is designed as an RC structure with a steel spatial structure for the roof, which was manufactured using the Željezara Sisak Space System. The main designer was architect Faruk Kapidžić, and the author of the structure was Osman Morankić, the structural engineer. The main contractor was a company named Unigradnja, while the steel roof was realised by Metaling. Construction of the swimming pool began in 2005 and was completed in 2008 with the official opening. In the meantime, the production and assembly of the steel structure took about 6 months. The interior of the swimming pool with an illustration of the roof can be seen in Figure 20.

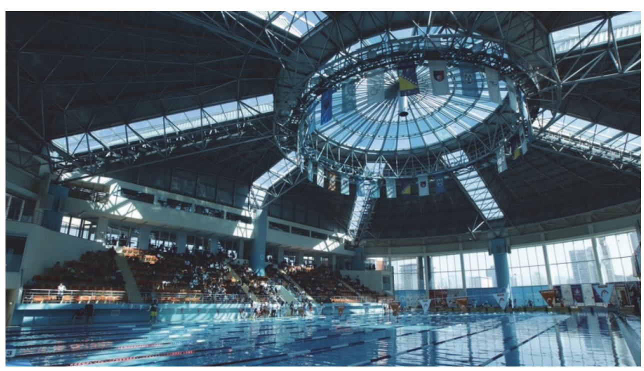

Figure 20. Otoka Olympic Pool's interior [20]

The roof of the pool is conceptually a dome whose main ribs consist of triangular trusses connected to a central lattice ring equipped with a walkway and topped by a skylight. The steel spatial truss supporting the roofing is mounted on the ribs of the dome and is also supported by an RC structure. Figure 21. shows part of the roof from the assembly phase of the steel structure.

Figure 21. Partial view of the roof from the assembly period

The ground plan dimensions are 63.4 x 44.8 metres, and the area is approximately 2940 m^2. The total number of tubular members is 2688 and the number of nodes is 734. The roof structure is supported by 8 columns on the RC structure. The cross-sections of the tubes vary between 60.3 mm and 219.1 mm in diameter. The weight of the roof structure is 174 tonnes, of which 115 tonnes are accounted for by the spatial structure, whose surface weight is therefore 39 kg/m^2.

6. Conclusion

The design of the MERO-type steel spatial structures is relatively intuitive. The design of each individual tubular member, i.e. the assignment of optimum cross-sections from the catalogue, represents an advantage in terms of minimising the self-weight, but also in terms of visual tracking the transmission of forces through the spatial truss. When looking at a fully designed truss, it's possible to recognise the dominant load locations and track the load transfer to the supports by following the member sizes, which enables a quick engineering check of the global load-bearing concept.

What makes the design of these structures difficult is the lack of modern software that facilitates the design and makes it organised and complete. Currently, the process is divided into the design of members and the design of spheres, both of which are carried out using automatic design tables in conjunction with structural analysis software. The aforementioned tables and other old specialised computer programmes aren't commercially available, which further limits the use of the MERO system.

To summarise, MERO structures, when their design conditions are met, have been proven to be very lightweight structures that retain the property of lower weight compared to other structural systems despite the exceptionally large spans. As the weight of MERO-type structures increases due to greater loads, the weight of other competing structural systems also increases, but they generally cannot offer the ease of transport and erection and the impression of spatial transparency as MERO-type structures with their exceptionally slender.

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