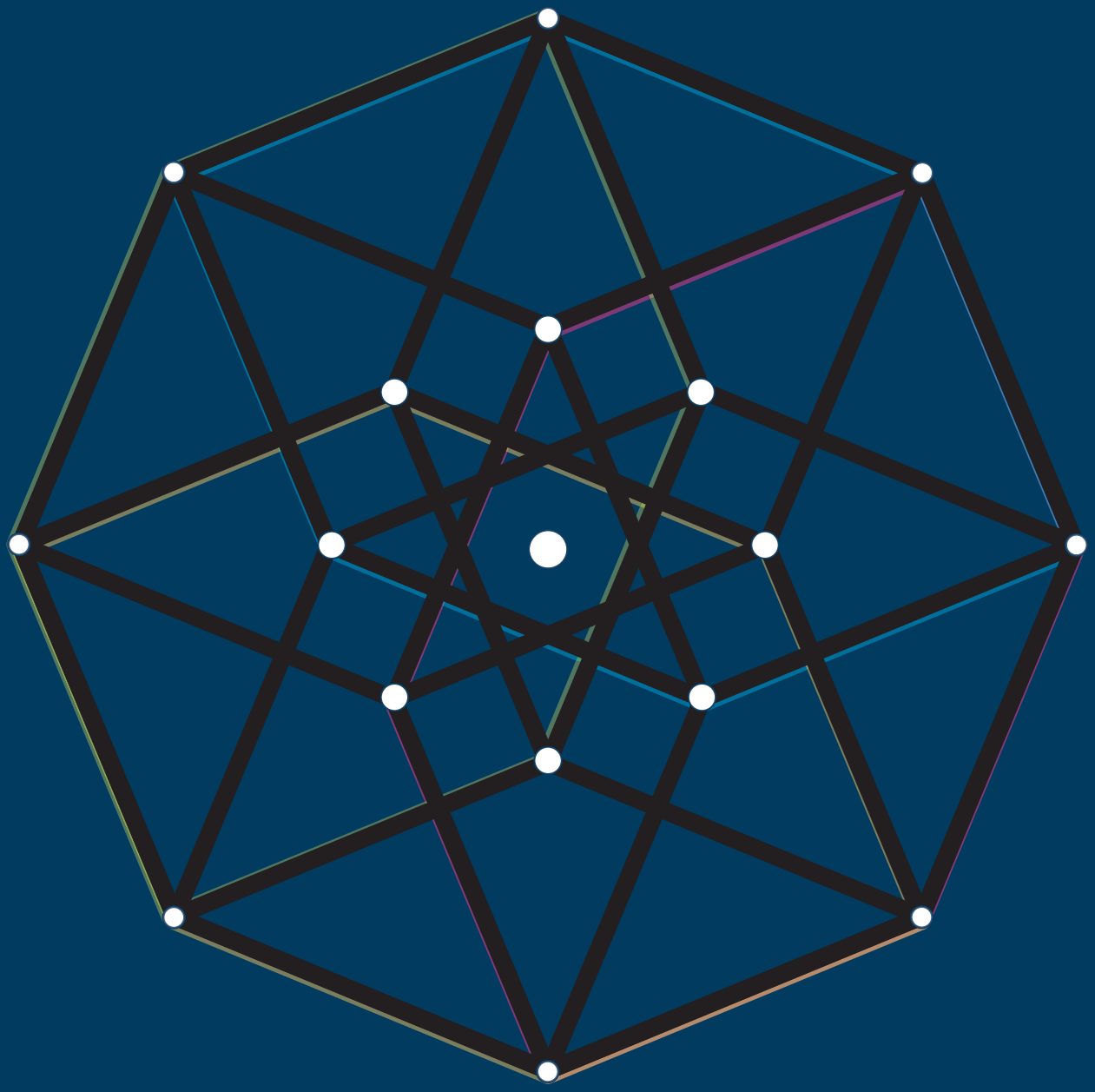


ЗБОРНИК НА ТРУДОВИ
PROCEEDINGS

ГРАДЕЖНО КОНСТРУКТОРСТВО – БЕЗ ОГРАНИЧУВАЊА
STRUCTURAL ENGINEERING – LIMITLESS

ДГКМ
ДРУШТВО НА ГРАДЕЖНИ КОНСТРУКТОРИ НА МАКЕДОНИЈА

MASE
MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS

21 МЕЃУНАРОДЕН СИМПОЗИУМ
INTERNATIONAL SYMPOSIUM

ОХРИД, С. МАКЕДОНИЈА
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24 - 27 септември 2025
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Macedonian Association of Structural Engineers
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STRUCTURAL ENGINEERING – LIMITLESS

Structural engineering is a specialized subset of civil engineering, a traditional engineering discipline dating back to ancient civilizations. Structural engineers ensure that structures can withstand the loads and stresses imposed by use and the environment throughout their intended lifespan. They combine knowledge of mathematics, physics and material science with practical design and construction methods to deliver safe, stable, durable, cost-effective, energy-efficient, and sustainable structures. Structural engineers also inspect and assess structures, and when damage or deterioration is detected, they act as forensic engineers and are often the first on site. Their responsibilities also include following the latest building codes and standards.

Today, the world is changing faster than ever. Tradition meets transformation. We are standing on the threshold of a new age, where cutting-edge technologies are reshaping the way we design, construct, and maintain structures.

At the heart of these changes are key advances in data-driven concepts, sensor technology, and the Internet of Things (IoT) in the AEC sector, as well as sustainability in construction materials - each pushing the frontiers of structural engineering beyond previously imagined limits. How do we enable smarter, more efficient design processes? Can we revolutionize the way we monitor and maintain structures in real time, unlocking new possibilities for predictive modeling and optimization? Can we create intricate, highly customized building components with unprecedented precision while bringing structures to life in virtual spaces, providing powerful insights, and fostering proactive decision-making?

The possibilities are truly limitless.

While digitization in our sector is about transferring the design documentation and drawings into digital formats, digitalization goes far beyond that. It is about automating processes, connecting disciplines, creating intelligent ecosystems that redefine collaboration, and simulating the entire lifecycle of a structure. Building Information Modeling (BIM) allows us to design and coordinate with architects and other engineers in real time, reducing errors, saving time, and enabling data-driven decisions from conception to demolition. Submitting BIM models to authorities can enable a fully automated process of rules and codes compliance checking, thus ensuring efficient and transparent issuance of digital permits. These models, when integrated with geographic information systems (GIS) and smart city platforms can become the digital source of truth.

Digital twins are living mirrors of real structures. They continuously integrate real-time data from sensors, equipment, and systems to simulate performance, detect anomalies, and predict and prevent potential failures. The sensors we integrate into structures act like their nervous system: they sense sudden environmental changes or load increases and send alarm to owners. With the IoT, the infrastructure becomes interconnected, communicates in real time, exchanges data, and predicts future behavior.

Unlike generative AI and most common Large Language Models (LLM)-based AI which cannot significantly transform the AEC sector, AI agents can perform multi-step tasks autonomously. They can act, plan, iterate, run scripts, generate models and FE mesh, call FEM solvers, read BIM files, and even evaluate results. If LLM-based AI can be our assistant, the future will show whether AI agents can become members of our teams.

Today, we design and build not only with physical materials, but also with data as a new building material. However, while our intuition as structural engineers can be guided by data, we should do the critical thinking, visionary design, and leading and controlling the design process.

Prof. Darko Nakov,



President of MASE

21st INTERNATIONAL SYMPOSIUM OF MASE
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LOAD TESTING OF STEEL STRUCTURE IN DOBOJ

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ABSTRACT

Load testing is a key method for verifying the safety and serviceability of civil engineering structures, particularly where analytical models cannot fully reproduce in-situ behaviour. This study assessed the performance of a newly constructed 34.4-m steel roof truss of the sports hall in Doboj under simulated snow load, with a focus on confirming elastic response and identifying potential weaknesses.

The testing followed JUS U.M1.047 and the relevant technical regulations. Mechanical deflectometers (dial gauges) were used to measure deflections at critical joints, while terrestrial laser scanning (TLS) provided spatial deformation data across the truss. This combination enabled precise local measurements together with global monitoring of the structure.

Measured deflections remained below the calculated values, and residual displacements were within prescribed limits, confirming elastic behaviour. No cracking, slip, or loosening was detected at the bearings or in the bolted connections, verifying technical adequacy. In contrast to some comparable case studies, the truss exhibited little reserve load-bearing capacity and operated close to its design limit. Joints and connections were identified as the most sensitive components. TLS proved valuable as a complementary monitoring technique, while mechanical deflectometers remain the most reliable tool for deformation assessment.

For safe operation, periodic inspections of steel joints and concrete supports are recommended, along with deflection checks at critical points. Occasional application of TLS and systematic documentation can support long-term structural health monitoring. These recommendations are broadly applicable to similar large-span steel structures.

The Doboj truss meets the technical requirements and can be considered safe for service. The presented results and guidelines contribute both to the scientific literature and to practical procedures for load testing of large-span steel structures.

Keywords: steel steel roof truss; load testing; experimental measurements; terrestrial laser scanning (TLS).

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1. INTRODUCTION

Experimental load testing of structures is an important part of the overall process of designing, constructing, and operating civil engineering works. It enables the collection of data that are crucial for verifying design assumptions, assessing the reliability and safety of the structure in service, and timely detection of any deficiencies that could compromise its functionality or durability [1], [2], [3], [4]. In domestic engineering practice, in addition to bridge testing, there is a series of notable examples of successfully executed static load tests on other building structures with significant spans [5], [6], [7], [8].

This paper presents the static load testing of the main steel roof truss of the sports hall in Doboj (Fig. 1 and 2). The test was conducted after the completion of construction works on the roof structure and prior to the installation of building services (MEP). Its primary purpose was to confirm the load-carrying capacity of the structure with respect to the design service loading (with snow load taken as governing), as well as to verify the conformity of workmanship quality with the technical documentation.



Fig 1. Sports hall in Doboj, exterior view



Fig 2. Sports hall in Doboj, roof truss configuration

The testing was carried out in accordance with JUS U.M1.047 - Testing of building structures by proof loading and testing to failure [9], and with the provisions of the Rulebook on technical regulations for inspection and testing of steel structures (Official Gazette of the SFRJ, no. 6/65) [10]. The load was applied in a total of five stages (four loading stages with an intermediate stage, explained in more detail below), up to the level specified in the design. The truss was executed predominantly with welded connections, while bolted splices were used at certain joints of the bottom and top chords. On the first day of testing, the load was applied in two stages. Already in the first stage, an excessive deviation of measured deflection from calculated values was observed beneath one bolted splice, which required unloading of the truss after the second stage and subsequent re-loading to verify the integrity of this splice. On the second day, the load was incrementally brought to the full design value, after which the structure was unloaded and residual deflections were recorded.

The behaviour of the truss was monitored using mechanical deflectometers as well as terrestrial laser scanning.

2. LOAD TESTING PROGRAM

Before commencing the proof load test of the main roof truss, a review was performed of the relevant portions of the design documentation pertaining to the roof structure, together with the submitted quality-control documentation for the executed works on the main roof truss; a visual inspection of representative main roof trusses – and all of their members – was carried out, and a detailed testing protocol was prepared.

The testing protocol defined the measurement locations, the loading stages, the expected maxima of internal effects and the calculated deflections by stage at the test locations. It also specified the layout of the working platform, the magnitude and position of the proof load for each stage, and the choice of test load. The load magnitude was set to correspond to the service (design) loading, i.e., snow weight on the hall roof of 1,25 kN/m², with efficiency with respect to deflections close to unity (1,02).

During the test, vertical deflections were measured at each loading stage, and permanent (residual) deflections were measured after unloading. A detailed visual inspection of the roof truss as a whole was conducted before loading, under the full applied proof load, and after unloading.

Deflections were measured with mechanical deflectometers; in addition, geodetic observations of the entire truss, as well as adjacent trusses, were performed using terrestrial laser scanning [11]. The primary measurements were taken with mechanical deflectometers, which tracked deflections in real time during the test. The laser-scanning results were analyzed post-test to verify overall truss displacements and to monitor the movements of neighboring trusses.

Terrestrial laser scanning represents a state-of-the-art technology for mass acquisition of spatial data in the form of point coordinates. A very large number of points can be captured with high accuracy in a relatively short time. This technique is increasingly used for assessing the condition and for monitoring the displacements and structural behaviour of existing structures [12], [13], [14].

2.1. Structure Characteristics

The roof structure of the subject hall consists of seven primary steel roof trusses, each 34.44 m in length, spaced at a centre-to-centre distance of 7.25 m. Purlins are supported at the truss panel points at a centre-to-centre spacing of 2.89 m, with bracing provided in the roof plane and additional bracing in the plane of the bottom chord of the main truss. The layout of the hall roof structure is shown in Fig. 3.

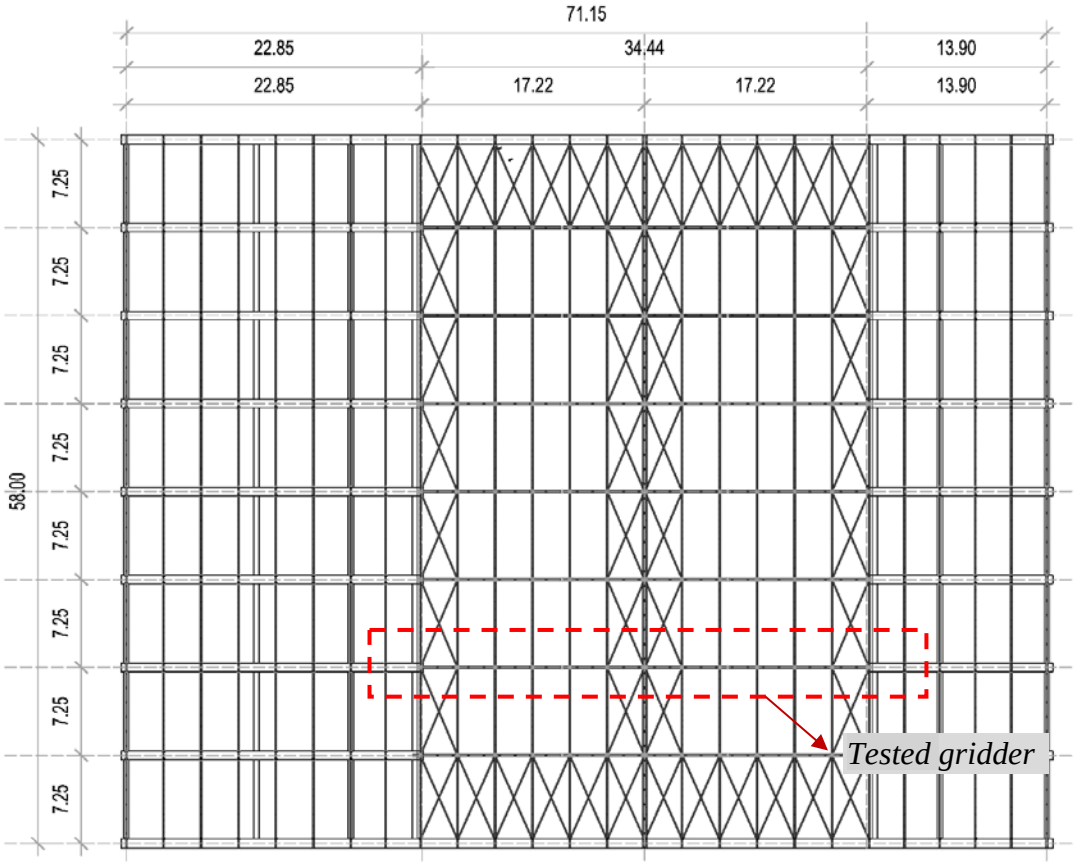


Fig 3. Layout of the hall roof structure and position of the truss subjected to testing

The main trusses are fabricated from welded [channel sections and square hollow sections of steel grade Č.0361. The truss depth is 3 300 mm, with panel points set at a horizontal spacing of 2 890 mm.

2.2. Test Load Characteristics and Load Transfer to the Truss

The proof load consisted of 25 kg cement bags placed on pallets on a specially fabricated steel platform (mass ≈ 1.5 t), which was suspended from the truss at the panel points by means of ribbed reinforcing steel bars (Fig. 4 and 5).



Fig 4. Load transfer to panel points via ribbed reinforcement bars

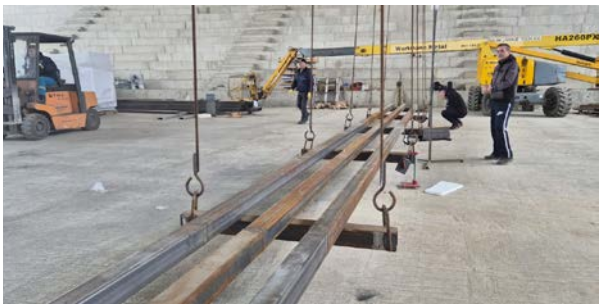


Fig 5. Loading platform

2.3. Loading phases

On the first day of testing, the load was applied in two stages up to about 50% of the design proof load, after which the main truss was unloaded. On the second day, the load was applied in three stages up to the full governing design value, and then removed in stages until complete unloading. The total load for each stage is listed in Table 1.

Table 1. Total load by loading phases

	Day 1				Day 2				
Loading phase	LP* 0	LP 1	LP 2	UP**	LP 0	LP 2’	LP 3	LP 4	UP
Total load	0.0	60.6	101.0	0.0	0.0	121.2	153.4	211.8	0.0

* loading phase **unloading phase

The load arrangement is shown in Fig. 6.

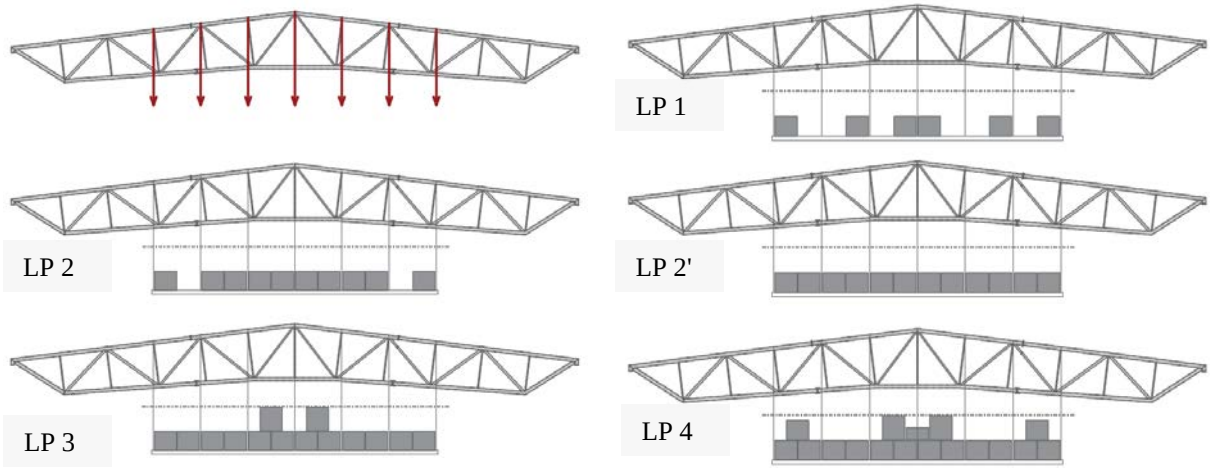


Fig 6. Method of applying the proof load and schematic load distribution by stages

The maximum prescribed proof load remained on the structure for 4 h, as required by the standard for steel structures, during which periodic measurements were recorded.

2.4. Deflection Measurements

Deflections were measured with *Huggenberger* mechanical deflectometers, with an accuracy of 0.005 cm. Deflections were directly measured beneath the supports and at characteristic points along the truss. The arrangement of the mechanical deflectometers is shown in Fig. 7.

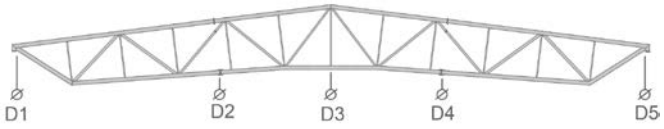


Fig 7. Layout of measurement points for deflection measurements with mechanical deflectometers

Geodetic scanning was performed with a *FARO Focus M* terrestrial laser scanner on both testing days, from a total of 26 stations and with approximately 900 000 000 points captured. A resolution of 1.5 mm at 10 m was adopted. Scanning was performed without georeferencing, using spherical targets. Registration of the 26 individual point clouds was conducted in *FARO Scene* using the spherical targets. Each successive cloud contained at least three common spherical targets, on the basis of which all points were transformed into a single (local) coordinate system. The scanning plan is shown in Fig. 8.

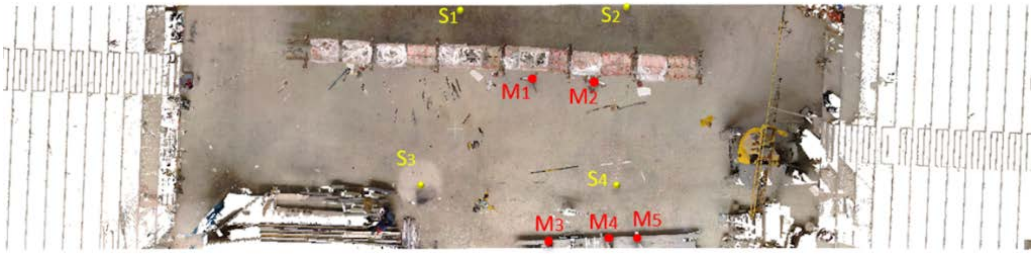


Fig 8. Scanning plan – station layout (S1–S4) and spherical target layout (M1–M5)

3. LOAD TESTING RESULTS

For each loading stage, changes in deflection over time were recorded. After each stage, readings were taken multiple times and, once stabilization had been confirmed, the governing deflections were registered. The next loading stage was applied only after it had been established that there was no increase in instrument readings over 15 minutes.

After excessive deflections were observed beneath a bolted splice at measurement point 4 on the first testing day, the truss was unloaded following the second stage, and on the following day the load was reapplied up to the full value. The load–displacement diagram for day 1 shows irregular behaviour of the bolted splice at measurement point 4 (Fig. 9, left). On day 2, linear behaviour is evident at all measurement points (Fig. 9, right).

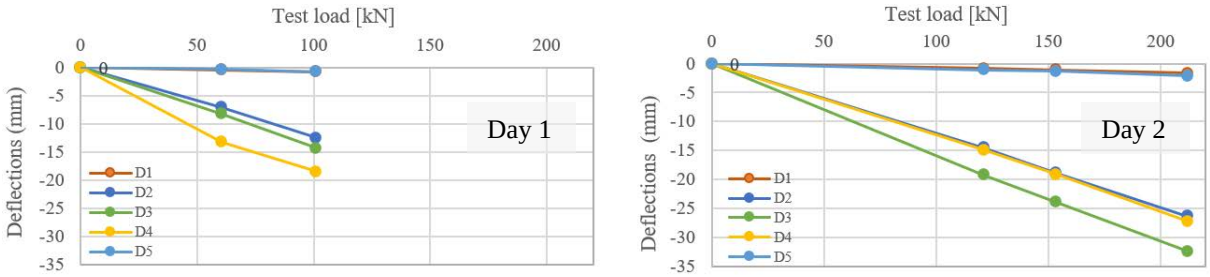


Fig 9. Graphical load–displacement relationships by testing stages: day 1 (left), day 2 (right)

Photographs of the proof load by stages for both days are shown in Fig. 10.





Fig 10. Proof load by loading stages

2.5. Deflection Measurements Results

The total displacements of the measurement points are shown graphically (Fig. 11). The relative displacements of the truss measurement points, excluding the movements of the cantilever supports, are shown in Fig. 12.

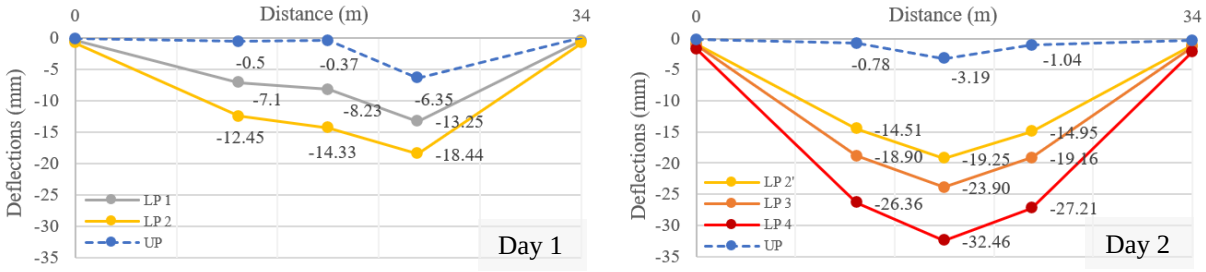


Fig 11. Total displacements of measurement points, day 1 (left), day 2 (right)

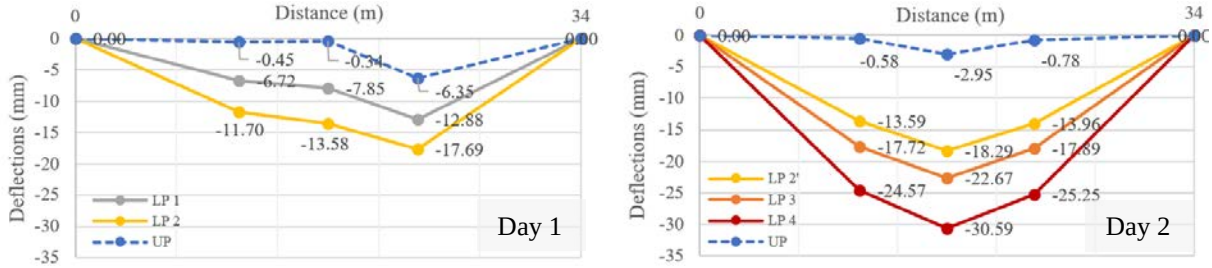


Fig 12. Relative displacements of measurement points, day 1 (left), day 2 (right)

Following a review of the laser-scanning images (Fig. 13), the analysis of point displacements of the truss relative to the zero stage was carried out for the bottom chord using the *Cloud-to-Cloud Distance* tool in the *CloudCompare* software package (Figs. 14 and 15). This method enables quantitative comparison of two point clouds by, for each point in the target cloud (loading stage), finding the nearest point in the reference cloud (zero stage) and computing the Euclidean distance between them along the coordinate axes. The result is a set of spatial differences that allows tracking of deflection changes along the entire truss.

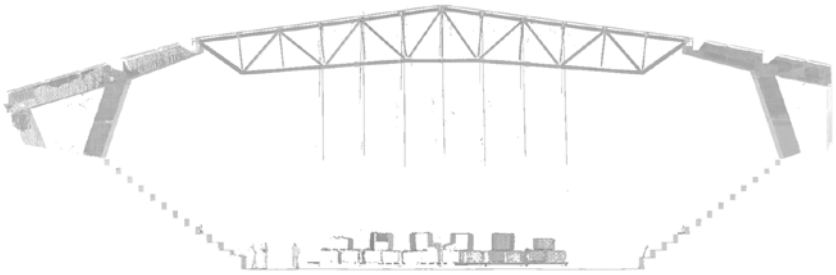


Fig 13. Laser-scanning image of the loaded truss

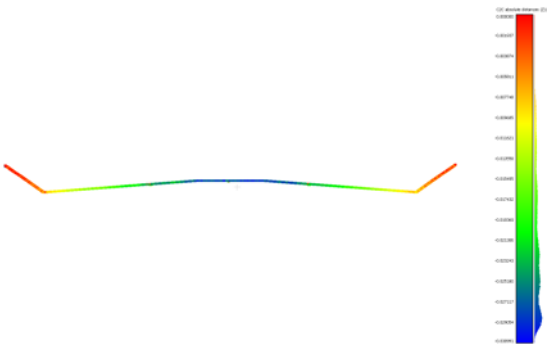


Fig 14. Bottom-chord displacements for LP 4

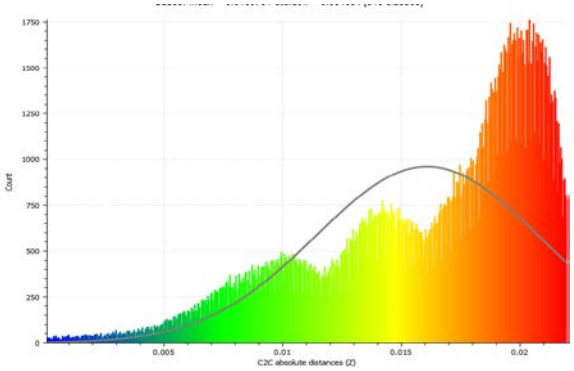


Fig 15. Histogram-based analysis of displacement scatter for LP 4

2.6. Result Analysis

The fundamental criterion of technical adequacy after testing is that the measured deflections and deformations under the proof load must not exceed the calculated values for the same load. The structure must exhibit elastic behaviour, meaning that residual deformations and deflections after unloading must fall within the limits prescribed for the given structure type. For steel and composite structures, residual deformations and deflections must not exceed 15% of the maximum measured values at the same point during proof loading.

Table 2 presents comparisons of calculated values with the values measured by mechanical deflectometers, together with the residual deflections. The calculated values were obtained by a verification static analysis in the *Tower 8.5*. The table shows the corresponding stage-by-stage displacements for an analytical model with rigid supports, under loads equivalent to those applied during the test.

Table 2. Comparison of calculated and measured deflections

		Measured maximum deflections (mm)	Calculated deflections (mm)	Difference in calculated and measured deflections (mm)	Residual deflection (mm)	Residual deflection (%)
Day 1 of load testing						
LP 1	D2	-6.72	-7.65	0.93	–	–
	D3	-7.85	-8.53	0.68	–	–
	D4	-12.88	-7.76	-5.12	–	–
LP 2	D2	-11.70	-13.21	1.51	-0.45	3.83
	D3	-13.58	-14.68	1.10	-0.34	2.54
	D4	-17.69	-13.21	-4.48	-6.35	35.90
Day 2 of load testing						
LP 2’	D2	-13.59	-15.74	2.15	–	–
	D3	-18.29	-17.32	-0.97	–	–
	D4	-13.96	-15.74	1.78	–	–
LP 3	D2	-17.72	-20.18	2.46	–	–
	D3	-22.67	-22.52	-0.15	–	–
	D4	-17.89	-20.18	2.29	–	–
LP 4	D2	-24.57	-27.74	3.17	-0.58	2.34
	D3	-30.59	-30.70	0.11	-2.95	9.66
	D4	-25.25	-27.74	2.49	-0.78	3.07

On the first testing day, at measurement point D4 (location of the bolted splice), the deflection exceeded the expected calculated value by 5.12 mm, or 66%, already in the first loading stage, and by 4.48 mm, or 33.9%, in the second stage. After unloading, a residual deflection of -6.35 mm was measured at this location, corresponding to 35.9% of the maximum deflection. This behaviour is consistent with expectations for a bolted splice. For members executed entirely with bolted connections, standards recommend reapplying the full design load after unloading to eliminate permanent set in the bolted joint.

On the second testing day, the results show that the deflection values satisfy the requirements of the standard; that is, they do not exceed the deflections obtained by the verification analysis in any loading stage. At the stage of maximum load (LP 4), all measured deflections are smaller than the deflections from the verification analysis. All residual deflections are below the permitted 15%, and it can therefore be concluded that, for the applied load, the steel truss is operating within the elastic range.

The overall deflection values measured by terrestrial laser scanning are consistent with those obtained using mechanical deflectometers and are lower than the values from the verification static analysis.

2.7. Visual Inspection of the Truss

It is essential to ensure during testing that the efficiency coefficient of the proof load (the ratio of the applied static proof load to the calculated governing load) is not less than 1, so that the structure is brought to the state corresponding to full service loading. In this way, the behaviour of all members, their joints, and the bearings can be clearly assessed.

Namely, if something is deficient, it is preferable that it fail under test so that repairs can be executed in a timely manner before commissioning. Conversely, with a reduced proof-load intensity, all potential deficiencies may not be detected, which can be very dangerous for the structure and its users.

In the present case, a satisfactory efficiency coefficient with respect to deflections was achieved. This confirms compliance with the requirements of standard SRPS U.M1.047 and the ability to assess all – even non-instrumented – parts of the structure, including joints and connections.

Inspection of the bearings after unloading established that there were no cracks or other damage to the short reinforced-concrete bearing elements following application of the proof load. Likewise, no slip or bolt movement was observed on the steel plates – particularly in the zone of the sliding bearing where the main roof truss is connected to the reinforced-concrete structure (Figs. 16 and 17).

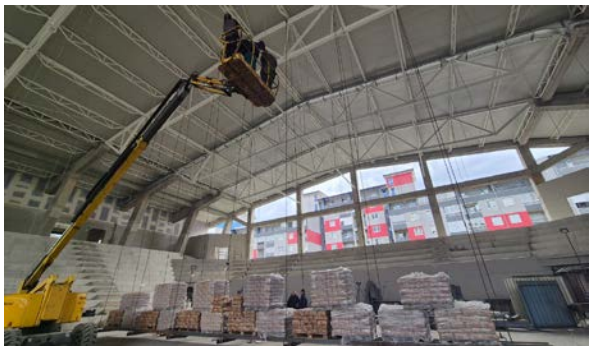


Fig 16. Inspection of the truss under full load



Fig 17. Detail of the truss sliding bearing

4. CONCLUSIONS

The steel roof truss of the sports hall in Doboj was proof-load tested in accordance with JUS U.M1.047 Testing of building structures by proof loading and testing to failure and with the Rulebook on Technical Regulations for the Inspection and Testing of Steel Structures (Official Gazette of the SFRJ, no. 6/65).

The analysis shows that the measured deflections do not exceed the calculated values obtained from the software model. Residual deflections are below the prescribed limits, confirming elastic behaviour. No undesirable deformations or loosening of connections were recorded. The bearing elements exhibited neither cracking nor bolt slip. All indications point to the technical adequacy of the structure for the intended service loading.

The results, however, differ from the authors' previous experience. In other tests of steel truss systems, it is often confirmed that as-built structures possess reserve load-bearing capacity exceeding the calculated values; in the present case, such reserve capacity was not observed. At the maximum design load, the truss operates close to its capacity limit. This finding confirms that joints and connections remain the most sensitive parts of the system and require special surveillance to prevent the consequences of possible progressive failure.

The application of terrestrial laser scanning (TLS) provided useful information on the spatial behaviour of the structure. The method enables detailed tracking of the displacements of all points of the truss and adjacent elements; however, it cannot be recommended as the primary or sole method for tests of this type. In this respect, measurements with mechanical deflectometers remain the most reliable means for deformation assessment.

Based on the foregoing, it can be concluded that the steel roof truss of the sports hall in Doboj meets the requirements of technical adequacy. The structure demonstrates a satisfactory level of safety and functionality for the intended loading, but without significant reserve load-bearing capacity. For safe operation and long-term reliability, the following are recommended: periodic visual inspection of steel joints and bolted connections with attention to possible slip and loosening; inspection of reinforced-concrete bearing elements for timely detection of cracks; periodic checks of deflections at critical points using deflectometers; supplementary application of TLS at longer intervals to monitor global behaviour; and systematic record-keeping and analysis of all inspections and measurements to establish a continuous monitoring system.

In this way, the structure can remain stable, functional, and safe for use in the future.

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