Journal of Kryvyi Rih National University
Journal homepage: https://journal-knu.com.ua/en
Article's History: Received: 11.07.2025 Revised:20.10.2025 Accepted: 24.12.2025 Published: 28.12.2025
Vol. 23, No. 2, 2025
ISSN 2306-5451
e-ISSN 2519-2736

UDC 624.014.2:624.072.2
DOI: 10.31721/2306-5451-2025-2-23-81-88

Experimental study of the deformability of a truss with parallel chords

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Abstract. The aim of this study was to comprehensively investigate the deformative properties of a welded truss with parallel chords under field test conditions and to compare the experimental results obtained with the results of finite element modelling. The main focus was on determining the relationships between the magnitude of the applied load and the corresponding deformations (deflections) of the structure under the action of static external forces. Field tests were performed on a full-scale welded sample of a truss with parallel chords with a step-by-step static load from a hydraulic jack, with strain gauges and clock-type indicators installed at characteristic locations to monitor deformations and deflections, as well as simultaneous numerical modelling in the LIRA software package to obtain and compare load-deformation curves with the results of field measurements. The experimental data obtained included quantitative indicators of truss deflections at different levels of applied load, so that at a load of 0.35 t, the deflection is 25 mm, and with an increase in force to 1.05 t, the deflection increases to 118 mm. Load-deflection graphs were created, demonstrating the linear behaviour of the structure within the studied load range. A comparison of the experimental results with the finite element modelling data showed a high degree of consistency. The data obtained allow to refine the stiffness characteristics of the elements and increase the reliability of predictive calculations regarding the deformability of the structure. The developed methodology can be used to improve the accuracy of the design and calculation of welded trusses and to adapt design models to real operating conditions

Keywords: metal structures; welded structure; strength; deflection; load-bearing capacity; limit state; software package

Introduction

Flat trusses with parallel chords are widely used in various sectors of the economy. Such truss structures are often used in industrial and civil construction, in particular in the construction of public and industrial buildings, as well as elements of transport structures. In addition, trusses with parallel chords are used, in particular, in the automotive industry, and are also widely used in agricultural machinery manufacturing, etc. The widespread use of such trusses with parallel chords is due to a high degree of automation and ease of manufacture, along with an effective ratio of their own weight and load-bearing capacity. Thus, the issue of designing and calculating trusses is relevant. The use of modern software tools, such as LIRA-SAPR, makes it

Suggested Citation:
Kovalchuk, Ya., & Omelian, M. (2025). Experimental study of the deformability of a truss with parallel chords. *Journal of Kryvyi Rih National University*, 23(2), 81-88. doi: 10.31721/2306-5451-2025-2-23-81-88.

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possible to implement variant modelling for structural strengthening. This is proven in the work of Y. Dmytrenko *et al*. (2025), which describes examples of effective numerical analysis of bending elements in complex engineering conditions. In general, a significant number of scientific works are devoted to experimental research of trusses. For example, the work of M. Basara *et al*. (2021) presents the results of experimental studies of the durability of a rectangular welded truss made of profile pipes using the technology of non-shaped nodes. The research was carried out using a computer simulation experiment in the ANSYS Workbench 17 environment and a semi-natural experiment. It was determined that the loss of load-bearing capacity of the truss due to operational factors occurs as a result of the formation of a fatigue crack in the K-shaped joint on the upper chord of the truss. The results of the semi-full-scale and computer simulation experiments were verified, and a 5.7% coincidence in fatigue damage indicators was established.

In D. Bannikov *et al*. (2024), the possibilities of the graphoanalytical method of constructing a Maxwell-Cremona diagram for determining internal forces in steel trusses with parallel chords were investigated. The objects of study were three typical shop building projects in the cities of Zbarazh, Novohrad-Volynskyi (renamed Zviahel in 2022), and Kryvyi Rih, in which planar steel trusses were used. The method was implemented in AutoCAD, and the results were compared with numerical analysis in SCAD. It was found that the average discrepancy between the methods does not exceed 3%, which indicates the high accuracy of the graphoanalytical approach. The authors emphasised its advantage in conditions of limited access to specialised software, especially when assessing the residual load-bearing capacity of damaged structures.

The work of A. Saimi *et al*. (2021) presented two variants of the numerical method – the differential quadrature finite element method (DQFEM) and its hierarchical modification – for analysing the dynamics of rotating shafts. Although the object of study is mechanical systems, the methods can be adapted for the analysis of steel trusses, especially when modelling vibration modes and dynamic stability. The authors demonstrated high accuracy and efficiency of calculations, which makes these methods promising for application in engineering structures where calculation speed and accuracy are important under complex boundary conditions. The article also contains a comparison with the classical finite element method (FEM), which allows evaluating the advantages of DQFEM in the context of steel truss optimisation. The work of M. Kamiński & R. Błoński (2022) was devoted to conducting field tests of steel trusses under real snow load conditions. Actual deflections, stresses and deviations from design values were determined. The results were used to refine regulatory methods and improve the accuracy of calculations. Fatigue testing of steel bridge truss elements was carried out in the work of A. Patnaik & T.S. Srivatsan (2023). Damage accumulation in welded areas was established. The authors investigated the effect of cyclic loading on durability and proposed design changes to increase the service life. Y. Wang *et al*. (2022) investigated a composite truss made of carbon fibre-reinforced polymer and steel tubes with parallel chords. Experimental and numerical results showed increased stiffness and load-bearing capacity. The model took into account real load conditions and geometry.

The work of S. Chen *et al*. (2020) was devoted to assessing the reliability of steel trusses filled with concrete under bending loads. The authors used statistical analysis methods to calibrate models from a study of bending behaviour. The work of V.H. Truong *et al*. (2020) proposed a machine learning method for assessing the reliability of steel trusses. Experimental data was used to train models, allowing the ultimate load to be predicted with high accuracy. The work of W.V. Silva *et al*. (2020), based on experimental studies, demonstrated an improvement in the stiffness and load-bearing capacity of a spatial truss when using concrete struts reinforced with steel and sisal fibre. The work of J.M. Lima *et al*. (2022) investigated truss-type connections in steel composite beams. Experiments have shown the effectiveness of new types of connections in increasing the strength of structures. The aim of the study was to evaluate the actual deformability of trusses with parallel chords, taking into account structural imperfections, and to assess the consistency of experimental results with theoretical calculations.

Materials and Methods

The field test of the truss was carried out in the scientific testing laboratory of building materials, products and structures at the Ternopil Ivan Puluj National Technical University. The truss was made of profiled bent-welded pipes. Loading during the tests was carried out using a hydraulic jack. Then, through a strain gauge using a clock-type indicator, the force P was transmitted to the crossbar, which evenly redistributed the load to the upper chord nodes of the tested truss. The loading diagram and truss fastening conditions are shown in Figure 1.

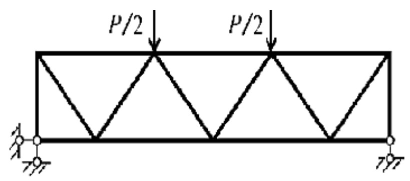

Figure 1. Diagram of the fastening and loading of the tested truss

Source: created by the authors

A welded truss 6 m long and 1.2 m high was mounted in a test bench for the purpose of experimental evaluation of its deformation characteristics under step loading (Fig. 2a). The experimental points were obtained by direct measurement of deflections under controlled conditions using calibrated displacement sensors, which ensures high reliability of the results. The magnitude of the applied force was controlled using a strain gauge force transducer with a clock-type indicator (Fig. 2b), which ensured prompt and accurate readings. The recorded load values were compared with the reference calibration data given in the strain gauge passport, which made it possible to verify the metrological accuracy of the measurements and confirm the reliability of the experimental series. The load was applied in stages: in the first stage, P = 0.35 t, in the second, P = 0.70 t, and in the third, P = 1.05 t. Time i ntervals were maintained between stages to stabilise the readings and minimise the influence of inertial vibrations. To record vertical displacements during loading, an additional clock-type indicator was installed in the central lower zone of the truss (Fig. 2c). In addition, another indicator was placed in the upper end part of the stand (Fig. 2d) to record displacements occurring in the area of the structure's support fastening. Such instrumentation ensured a representative reproduction of the kinematics of deformations both in the span and in the support areas with the appropriate spatial dispersion.

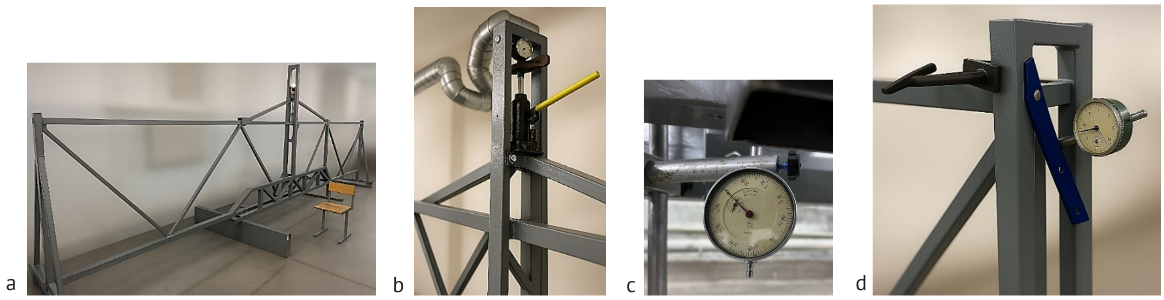

Figure 2. Iron ore enrichment system based on the Model 140 USIM PAC

Notes: a – general view of the test bench; b – diagram of force application and control; c – location of the indicator for measuring deflections; d – location of the indicator for recording displacements occurring in the area of the structure's support fastening

Source: created by the authors

To verify the data obtained experimentally, finite element modelling of the truss was carried out in the LIRA software package. Finite element modelling was performed using an adapted geometric model of the truss, taking into account the actual dimensions, material characteristics and boundary conditions close to the experimental ones. Figure 3 shows the points of application of loads of magnitude P/2, which correspond to the geometric scheme of the experimental model of the truss with parallel chords. The location of the loads, as well as their numerical characteristics and directions of action, were reproduced with high accuracy in accordance with the conditions of the physical experiment, which ensures the correctness of the comparison with the results of numerical modelling.

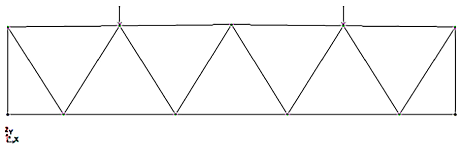

Figure 3. Load application points P/2 in finite element modelling

Source: created by the authors

The study used a comprehensive experimental and numerical methodology, which involved full-scale testing of a welded truss with parallel chords under controlled stepwise loading, combined with modelling of its behaviour in the LIRA software package. The numerical model was adapted to real geometric and boundary conditions, which allowed for a comparative analysis of experimental and calculated data.

Results and Discussion

As a result of a series of experimental tests performed using controlled step loading, a graphical dependence was obtained (Fig. 4), which reflects the change in the magnitude of elastic deformations of a steel truss with parallel chords during loading. This dependence allows a quantitative assessment of the structure's response to increasing loads and serves as a basis for further comparison with the results of numerical modelling. Thus, the experimental graph is a key element in the analysis of the stress-strain state of the structure under study.

The graph illustrates the dependence of the vertical deflection of a truss with parallel chords on the applied external load, obtained on the basis of experimental tests. At an initial load of 0.35 t, the deflection is 25 mm, and with an increase in force to 1.05 t, the deflection increases to 118 mm, which indicates a gradual decrease in the effective stiffness of the structural system. Thus, in the studied interval, a monotonic increase in deformations with an increase in load was recorded. Although the approximation by a linear dependence showed high consistency of data in the initial section, the nature of the curve in the load range above 0.70 t indicates a slight deviation from linearity. This nature of deformation growth may be due to the accumulation of plastic changes in the nodes and members of the truss, as well as secondary bending moments and local loss of stiffness. In addition, within the scope of the study, a graph of the deformation of a steel truss with parallel chords under the action of an external load P was constructed, obtained as a result of finite element modelling (Fig. 5). The distribution of elastic deformations of the truss at the loading stages, similar to the experimental tests, was visualised. This ensured the correctness of the subsequent comparative analysis of the results.

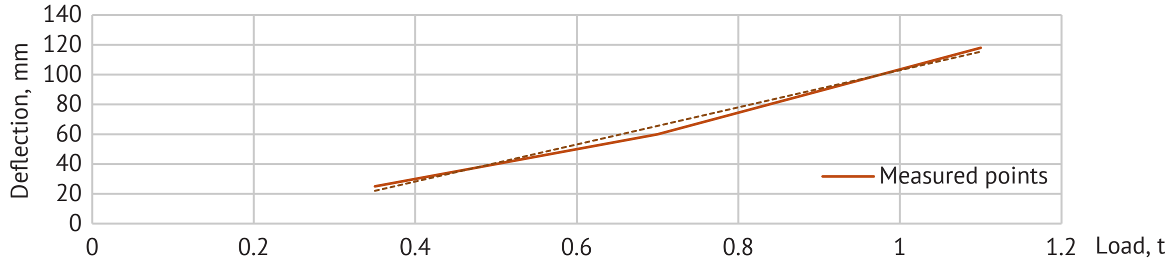

Figure 4. Dependence of elastic deformations of a truss with parallel chords on the action of a step load
Source: created by the authors

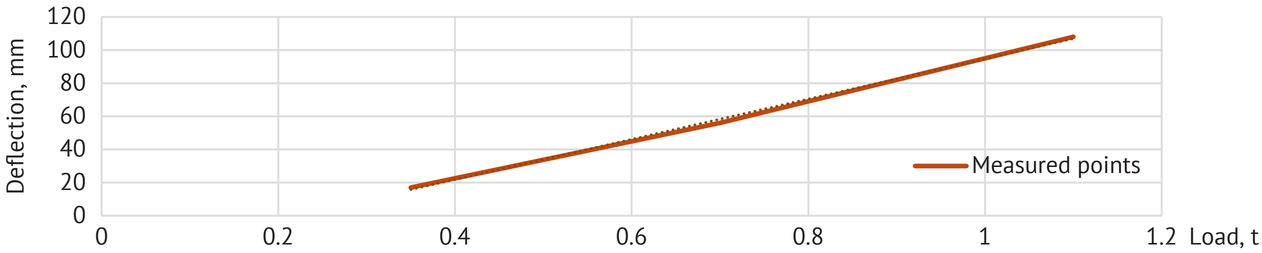

Figure 5. Dependence of elastic deformations of a truss with parallel chords on the action of step loading in finite element modelling
Source: created by the authors

The constructed graph demonstrated the dependence of the deflection of a truss with parallel chords on the applied load based on finite element modelling in the LIRA software package. At a load of 0.35 t, a deflection of 18 mm was recorded, at 0.70 t – 56 mm, and under conditions of 1.08 t, the deflection reached 108 mm. Such dynamics indicate an increase in deformations as the force increases, which indicates a gradual decrease in the stiffness of the system. The calculated deflections are smaller than those obtained in experimental tests. This effect is due to the presence of initial defects in the actual structure, which cannot be taken into account when modelling the operation of a truss with parallel chords in the LIRA software package. Figure 6 shows a comparison between the results of finite element modelling and experimental measurements of vertical deflections of a truss with parallel chords under the action of forces, which allows to evaluate the accuracy of numerical prediction of deformations within a load range of up to 1.05 t.

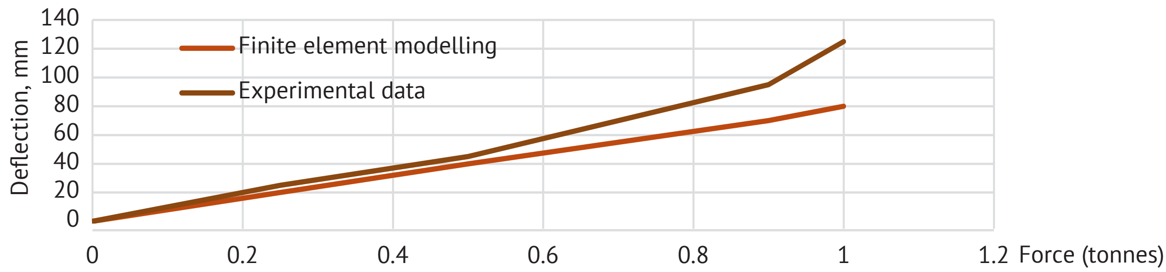

Figure 6. Comparative dependence of vertical deflection on load based on the results of finite element modelling and experimental tests
Source: created by the authors

The graphical representation of the results demonstrated the dependence of deflection on load for two series of data – finite element modelling and experimental tests – in the same load interval from 0 to 1.2 tonnes. Both curves increased monotonically with increasing force, maintaining an approximately linear shape throughout the range. This indicated predominantly elastic behaviour of the structure at a limit load of 1.05 t. The differences between the series were in the amount of deflection at each point. The finite element model gave lower values: at 0.35 t – 18 mm versus 25 mm in the experiment; at 0.70 t – 56 mm versus 60 mm; at 1.08 t – 108 mm versus 118 mm. The largest deviation (≈28%) was observed in the first stage, the smallest (≈7%) – in the middle stage. The model reproduced the stiffness of the structure with an error that decreased with increasing load.

FEM remains a key tool for assessing the stress-strain state and predicting the strength of steel and composite structures, as confirmed by numerous studies (Kovalchuk *et al.*, 2020; Basara *et al.*, 2021; Shynhera & Shved, 2023). In the vast majority of cases, FEM provides high modelling accuracy, flexibility in changing design parameters, and advanced capabilities for visualising stress and strain fields. These advantages make it an effective tool, particularly for complex truss systems and frame-rod schemes. At the same time, a comparison of the results of numerical analysis with full-scale experiments reveals a number of important limitations. In particular, stress concentrations, local bending effects, and the influence of initial defects in elements are often underestimated in the modelling of complex node areas. This is confirmed in the work of A. Schumacher & A. Nussbaumer (2006), where tests of full-scale K-shaped truss nodes revealed the significant role of out-of-plane bending components, which numerical models without special calibration reproduce insufficiently accurately.

A comparison of reinforcement options showed that even a slight change in the spatial position of the connections can change the stability by tens of percent. Similar patterns were observed in the author's modelling: local changes in the geometry or material of individual elements can significantly affect the distribution of stresses and the shift in natural vibration frequencies. An analysis of design approaches in seismic areas, performed by D.O. Bannikov *et al.* (2019), confirmed that the choice of truss type and stiffness of node connections significantly affects the actual stability of the truss. Although standard FEM models often describe these factors in a simplified form, real objects demonstrate more complex interactions between elements and a significant dependence on initial geometric imperfections. Modern approaches to the analysis of steel frames and trusses show a clear trend towards combining classical FEM models with probabilistic updating methods, machine learning, and advanced nonlinear formulations. In the work of T. Yaoyama *et al.* (2024), a probabilistic procedure for updating steel frame models is proposed, based on the joint use of deformation and acceleration measurements in a multitask Bayesian framework. Importantly, the update is performed in the modal space through the "displacement-stress" relationship, which reduces the dependence on prior knowledge of mass and increases sensitivity to localised damage, as confirmed by full-scale field tests of a steel frame.

There has been rapid development of tools that enhance the potential of FEM through machine learning and computational optimisation. In particular, T.V. Hung *et al.* (2019) demonstrated the possibility of significantly reducing prediction errors by using neural networks to reconstruct stress fields in areas with complex geometry. In more recent works, Y. Wang *et al.* (2022) emphasised the need to combine FEM with experimental validation when studying the stability and dynamics of spatial trusses, since it is complex approaches that ensure the correctness of modelling complex cyclic loads. The results obtained in this work are consistent with these conclusions, as they confirm the importance of experimental verification of FEM models even for relatively simple load schemes.

Hybrid "FEM + deep learning" methods for identifying the condition of structures have also undergone significant development. S. Bao *et al.* (2023) proposed a deep network with transfer learning, where training data was generated based on a calibrated FEM model of a steel frame, and then the knowledge of this network was transferred to a limited array of real monitoring data. It has been shown that for assessing the condition of steel frames with damaged bolt connections, the classification accuracy increases significantly (from ~82% to ~89%), with the specialised SHMnet architecture proving to be optimal, outperforming the classic VGG and ResNet types of networks. Thus, a clear bridge is created between physically based modelling and structural health data, which is especially important in cases where there is a shortage of field observations.

Another direction is the application of quantum computing for truss optimisation. The work of V.D. Nguyen *et al.* (2025) presents a hybrid framework in which a classical FEM solver is combined with quantum annealing to solve two related minimisation problems: for a mechanical boundary problem (minimisation of potential energy) and for updating design variables during the optimisation process. Although this study did not cover optimisation problems, the obtained load-deflection relationships can be used as reference constraints or criteria for verifying the correctness of optimisation algorithms, particularly in the context of the latest quantum-assisted methods. The proposed strategy of quantum-assisted sequential programming was demonstrated on several truss optimisation problems, showing the potential of quantum devices in cases where the dimension of the problem and the complexity of the constraints approach the limits of classical algorithms.

The issue of actual performance and progressive collapse of steel frames with composite decks is addressed in the work of J.P. Wei *et al.* (2025). The authors experimentally and numerically investigated the progressive failure of steel frames with factory-made steel truss decking with monolithic concrete slabs, modelling various scenarios of column removal and assessing the system's ability to redistribute forces. The results showed that the spatial mechanisms of the "steel frame + truss-concrete slabs" can significantly increase resistance to progressive collapse due to membrane effects and arch mechanisms, but require adequate modelling of the interaction between steel elements and reinforced concrete slabs. The FEM models constructed by the authors, calibrated according to the experiment, confirmed that simplified schemes can both underestimate and overestimate the stability margin depending on the chosen idealisation of connections, which is further confirmed by the study by O. Slipych *et al.* (2021).

A separate layer of modern research was devoted to the analysis of time series of SHM systems. The review work by C. Dzuwa *et al.* (2025) systematised deep architectures for the analysis of vibration and other time signals in the tasks of monitoring the technical condition of structures. The authors examined in detail recurrent networks (RNN, LSTM, GRU), convolutional models, hybrid CNN-RNN approaches, and transformers, focusing on the problems of noise, measurement gaps, the need to assess uncertainty, and data augmentation methods. An important conclusion was that most existing works remain either too focused on specific application cases or do not sufficiently consider the reliability and interpretability of models, which creates room for the integration of deep networks with physically grounded FEM models. In this context, the experimental and numerical study presented in this work can be considered as a source of physically interpreted reference deformation data obtained under controlled conditions.

Summarising the results presented, it can be argued that the current development of methods for analysing steel and composite structures demonstrates a move towards the integration of classical FEM models with advanced approaches – nonlinear formulations, probabilistic parameter updates, machine learning, and even quantum-assisted optimisation algorithms. All the studies reviewed confirmed that despite the high efficiency of FEM as an engineering tool, the reliability of predictions depends on the correct consideration of real structural features, initial defects, spatial stiffness inhomogeneities, and joint characteristics. Large-scale experiments, transfer learning methods, intelligent stress reconstruction algorithms, and modern approaches to the analysis of SHM system time series have reinforced this statement, demonstrating that combining physically based modelling with field observation data allows for significantly higher accuracy in assessing the stability, dynamics, and residual strength of structures. Thus, the modern scientific context has clearly indicated the need for multi-level hybrid approaches that combine the advantages of FEM with experimental calibration, ensuring reliable modelling of complex engineering systems and increasing the reliability of estimates obtained in design practice.

Conclusions

The study presented and tested a comprehensive method for field testing of a flat welded truss with parallel chords made of bent welded pipes, combining controlled step loading, force control with a strain gauge, and independent recording of displacements in the span zone and in the support zone. The methodology ensured reproducible measurements of deflections at three fixed load levels, correct comparison with the numerical model, and the ability to determine the limit of predominantly elastic behaviour of the structure. The obtained load-deflection relationships showed a monotonic increase in deformations with signs of deviation from linearity after reaching a load of about 0.70 t, which corresponded to the beginning of the accumulation of local plastic changes in the nodes and rods and/or the influence of secondary bending effects. Quantitative results of field measurements established deflections of 25 mm, 60 mm and 118 mm at loads of 0.35 t, 0.70 t and 1.05 t, respectively. The numerical model, performed in the LIRA software package, taking into account the actual geometric parameters, materials and boundary conditions close to the experiment, gave smaller deflection values (18 mm, 56 mm, 108 mm at the corresponding stages). The maximum relative deviation between the calculation and the experiment was observed at the first stage of loading (~28%), in the middle range it decreased to ~7-8%, and at the upper level it remained within the range of about 8-9%. This evolution of the discrepancy is interpreted as a manifestation of the system's sensitivity to initial geometric and technological imperfections (imperfections of nodes, initial deflections of elements, actual compliance of supports and node connections), which have a more significant impact on the initial part of the curve, while the increase in load "enhances" the role of stiffness distribution, which is better reproduced by an idealised model.

A comparison of the two data series demonstrated the suitability of the basic bar model for predicting deformability, taking into account the correction of initial conditions and refinement of the model of nodes and supports. It was established that in the range up to 1.05 t, the structure retains a predominantly elastic behaviour at the level of the global "load-deflection" response, however, local effects (stress-strain state in stress concentration zones, initial imperfections, microplasticity in welded joints) cause a decrease in effective stiffness compared to the idealised numerical scheme. This is important for verifying limit states for serviceability: numerical estimates of deflections without taking into account realistic defects may be conservatively underestimated. The proposed load scheme through the crossbar, calibrated force control and duplication of displacement measurement channels ensured high metrological reliability of the results at moderate resource costs. The prospect for further research includes the introduction of machine learning and statistical methods for automated assessment of the limit states of trusses and prediction of structural behaviour.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Експериментальне дослідження деформативності ферми з паралельними поясами

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Анотація. Метою даного дослідження було комплексне вивчення деформативних властивостей зварної ферми з паралельними поясами в умовах натурних випробувань та порівняння отриманих експериментальних результатів із результатами скінченно-елементного моделювання. Основна увага приділена визначенню залежностей між величиною прикладеного навантаження і відповідними деформаціями (прогинами) конструкції під дією статичних зовнішніх сил. Натурні випробування виконувалися на повнорозмірному зварному зразку ферми з паралельними поясами із поетапним статичним навантаженням від гідравлічного домкрата, з встановленням тензометричних перетворювачів і індикаторів годинникового типу на характерних ділянках для контролю деформацій і прогинів, а також із одночасним чисельним моделюванням у ПК «ЛІРА» для отримання та порівняння кривих «навантаження-деформація» з результатами польових вимірювань. Отримані експериментальні дані включали кількісні показники величин прогинів ферми при різних рівнях прикладеного навантаження, так при навантаженні 0,35 т величина прогину становить 25 мм, а з ростом зусиль до 1,05 т прогин збільшується до 118 мм. Сформовано графіки залежності «навантаження-прогин», що демонстрували лінійну поведінку конструкції в межах досліджуваного діапазону навантажень. Порівняння експериментальних результатів із даними скінченно-елементного моделювання показало високу узгодженість. Отримані дані дозволяють уточнити характеристики жорсткості елементів і підвищити достовірність прогнозних розрахунків щодо деформативності конструкції. Розроблена методика може бути використана для підвищення точності проєктування та розрахунку зварних ферм і адаптації проєктних моделей до реальних умов експлуатації

Ключові слова: металеві конструкції; зварна конструкція; міцність; прогин; несуча здатність; граничний стан; програмний комплекс