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# STRENGTH AND DEFORMATION ANALYSIS OF A WELDED TRUSS UNDER LOAD IN FIRE AND EMERGENCY TEMPERATURE CONDITIONS

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***Summary.*** *Welded trusses are widely used in civil engineering due to the optimal combination of high manufacturability and the ability to operate in various force scenarios. During operation, such structures are exposed to a complex impact of various technological and accident factors. This makes it difficult to determine the key parameters necessary for the smooth operation of the farms during the planned period of operation. Under the simultaneous influence of force and high temperature factors on the truss structure, damage may occur in structural elements and their joints due to changes in the mechanical properties of the material, which can lead to structural failure. To identify the features of deformation and fracture of the welded truss, full-scale experimental studies were performed for the physical model at temperatures of 20°C, 200°C, and 450°C. A computer modeling experiment was also performed for similar parameters of the impact on the truss. Based on the results of the full-scale and computer modeling experiments, we generated deformation graphs that make it possible to study the strength and deformability of the loaded welded truss at fire and emergency temperatures. A series of graphical dependencies characterizing the strength and deformability of the truss when it is loaded at different temperatures has been constructed. An analytical dependence has been developed that makes it possible to determine the value of the maximum permissible load on the truss at temperatures up to 450°C based on the known value of this load for room temperature conditions with a coincidence of 97.5...98.3%. It is advisable to use the obtained dependence (graphical or analytical) when designing or operating trusses to determine the maximum permissible loads on the structure at elevated temperatures.*

***Key words:*** *welded truss, temperature, metal structures, thermal effects, thermal deformations. local temperature effects, fracture mechanics.*

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**Statement of the problem.** Welded trusses, being fundamental components of numerous architectural and industrial structures, are subject to stringent safety standards. Typically, welded trusses have a rectangular configuration and are used in the construction of industrial, commercial facilities as intermediate supports for the installation of roof trusses in the spans between the load-bearing columns. However, such trusses can also support crane overhead conveyors, tracks etc. Modern engineering approaches address most exploitation issues by introducing additional safety factors that increase construction performance. But problem of combined force and thermal effects is complicated when the truss is also exposed to process temperatures. In some cases, this occurs when the temperature affects the entire building (metallurgical plant, foundry, rolling mill). However, the challenges posed by unforeseen events, such as fires or emergencies, demand a more nuanced understanding of how these structures respond under extreme conditions [1–3]. The complexity arises from dynamic interactions between thermal and mechanical stresses, posing challenges to the structural performance of welded trusses. This research seeks to fill critical gaps in understanding how stress distribution, concentration, and deformability evolve within the truss elements under the simultaneous effects of mechanical and high thermal loads.

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**Analysis of recent research.** In real-life scenarios involving structures exposed to fire, a intricate combination of mechanical strains arises from both applied loads and constrained thermal expansion. This results in cumulative mechanical strains that often surpass yield values, causing significant deformation. In contrast, the deflections of the structure are solely influenced by total strains. Therefore, in situations with high restraint, deflections may be minimal, but they are associated with extensive plastic deformation. Conversely, in cases with less restraint, larger deflections may occur, accompanied by a reduced need for plastic deformation and consequently, a lower compromise of the stiffness properties of the materials. These relationships imply that larger deflections might mitigate material damage and correspond to higher stiffness, while restraint may result in smaller deflections with lower stiffness. Such structural scenarios may seem counterintuitive when viewed through a conventional structural engineering lens [4]. Especially when taking into account the peculiarities of welded truss structures, such situations require detailed study.

**The objective** of this study is to comprehensively investigate the strength and deformability of a loaded welded truss under fire and emergency temperature conditions. The research aims to provide a detailed understanding of how thermal and mechanical stresses interact within the truss structure, with a specific focus on identifying stress distributions, potential vulnerabilities, and the deformability of the structure under extreme circumstances.

**Results of the research.** VSt3sp steel stands out as the most commonly used structural material in the construction of welded trusses due to its optimal combination of mechanical properties, weldability, and cost-effectiveness. Typically, it meets the necessary structural, technological, and operational requirements for such truss structures.

A crucial factor in ensuring the precision of calculations for a typical welded truss, regardless of the method employed, is the actual strength of the material. Given that trusses operate within the limits of elastic deformation, the yield strength of the material becomes a determining factor under these conditions. To assess the conditions leading to the limit state at the fracture point of the structure, the tensile strength of the material becomes a key strength indicator [5].

When evaluating the strength properties of VSt3ps steel based on quality certificates for a delivered batch of rolled metal, a considerable range of scattering in these strength properties was observed. This scattering was even more pronounced when considering values obtained from DSTU [6].

Consequently, it becomes evident that for a computer simulation experiment studying the behavior of an existing welded truss, precise results can only be achieved if the input information is based on the actual strength characteristics of the specific VSt3ps steel used in constructing the truss. Therefore, a rational approach to truss design involves acquiring rolled metal for manufacturing, determining its actual strength characteristics, and subsequently establishing the design parameters of the truss through computer simulation.

For a comprehensive experimental assessment, a set of standard specimens was created using rolled metal products from a single delivery batch intended for the production of welded trusses. The investigation into the strength characteristics of VSt3ps steel at elevated temperatures involved the utilization of standard specimens [7] placed within a thermal chamber (Fig. 1) of STM-100 test complex. The full-scale experiment covered a temperature range up to 450°C in increments of 50°C. Three specimens were employed for each temperature point, resulting in a total of 24 specimens for the entire temperature spectrum.

**Figure 1.** Thermochamber of the STM-100 test complex for determining the strength of VSt3ps steel at high temperatures

Based on the results of VSt3ps steel tests, a computer modeling experiment was performed for the entire welded truss truss at emergency temperature of 425°C and a simultaneously applied load of 100 kN and 230 kN according to the scheme provided (Fig. 2) and taking into account weight of the structure.

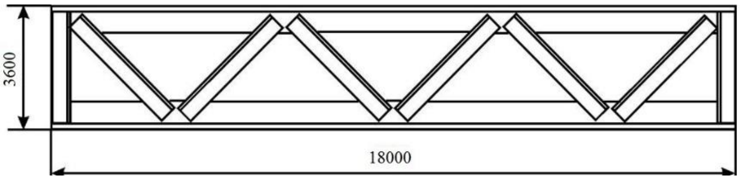
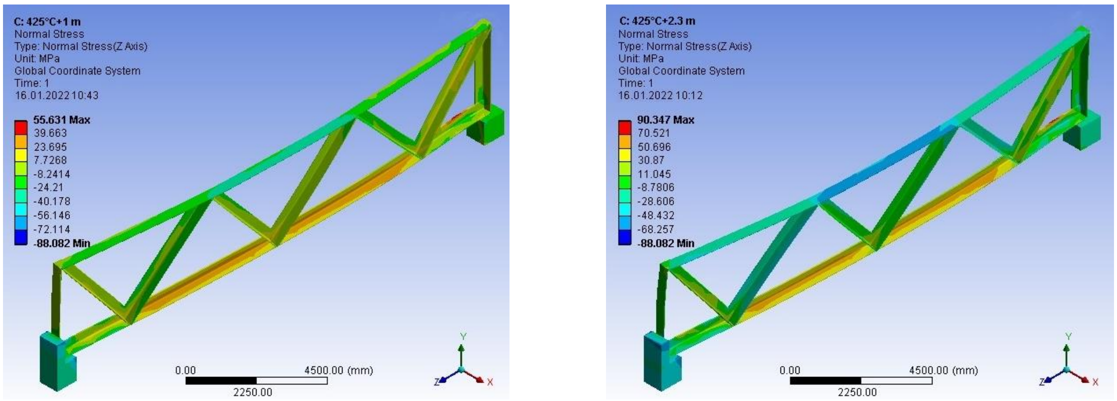


**Figure 2.** Welded truss specs

Based on the modeling results, a visualized qualitative picture of the distribution of equivalent stresses across the structural elements of the truss was obtained. It is obvious that the maximum tensile stresses are localized along the lower girders of the truss and compressive stresses in the middle part of the upper girders. Also visualization for the distribution of normal stresses across the elements of the welded truss when heated to 425O C and subjected to loads of 100 kN and 230 kN was obtained (Fig. 3). However, the area with the maximum stresses on the lower belt between the right support and intermediate nodes is already highlighted.



*a* *b*

**Figure 3.** Visualization of the distribution of normal stresses across the elements of a welded truss when heated to 425$^{O}$C and subjected to a load: a – 100 kN; b – 230 kN

As in the case of visualization of the stress distribution (Fig. 3) and the numerical distribution of normal stresses along the lower girders of the truss under various static loads at a fire and emergency temperature of 450°C (Fig. 4), it was found that the maximum stresses are localized in the lower girders in the area between the support and intermediate nodes on the side of the hinged-moving support.

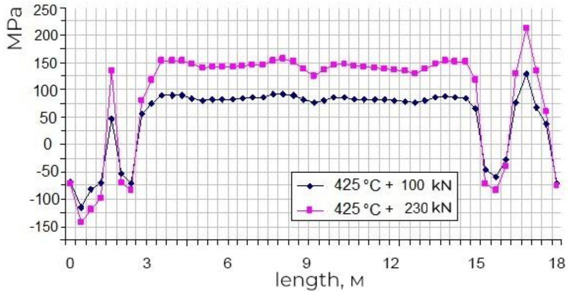


**Figure 4.** Distribution of normal stresses along the lower girders of the truss under different static loads at fire and emergency temperature of 450$^{O}$C

Moreover, their numerical values exceed the tensile strength of the material and will form the onset of the limit state for the test structure.

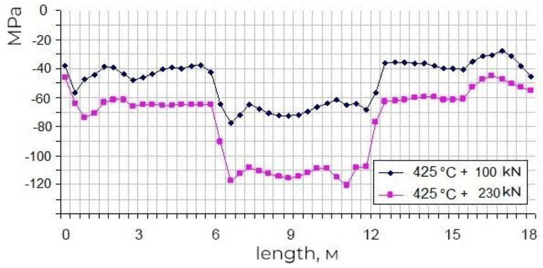
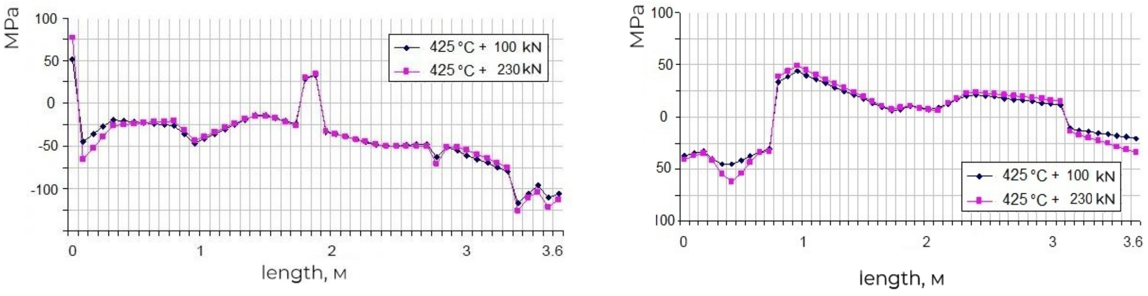


**Figure 5.** Distribution of normal stresses along the lower girders of the truss under different static loads at fire and emergency temperature of 450$^{O}$C

Obtained distribution of normal stresses along the left and right (Fig. 6) truss struts under different static loads at a fire-accident temperature of 450°C. Visually, the distributions differ from each other, but they are close in terms of the amplitude values of tensile and compressive stresses.



*a* *b*

**Figure 6.** Distribution of normal stresses along the truss under different static loads at a fire-accident temperature of 450$^{O}$C: a – left; b – right

The level of stresses formed in the posts when the truss is loaded with a force of 230 kN is not dangerous for the structure in terms of its strength. In all the braces, both tensile and compressive stresses occur, but, as in the case of the posts, their values are significantly lower than the yield strength of the material and they do not form a damaging effect on the truss.

The results of the analysis of the obtained stress distributions revealed that their maximum values are localized in the lower belt. It is the lower belt for the studied truss that determines the strength and deformability of the structure as a whole. To identify the deformation features of the lower belt of the welded truss at different temperatures, the simulation results were used to construct a diagram of the total elongation Δl of the lower belt of the truss (Fig. 7) and deflection δ in its middle (Fig. 8) under static loading at 20°C, 200°C, and 450°C.

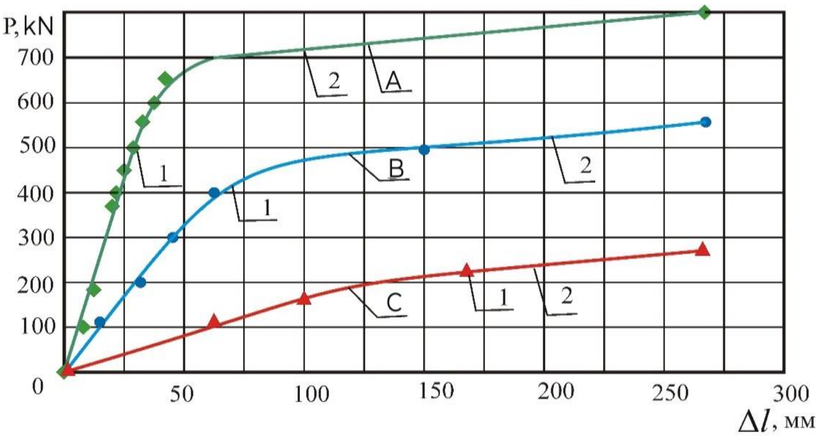


**Figure 7.** Diagram of the total elongation Δl of the lower truss belt under loading conditions: A – 20°C; B – 200°C; C – 450°C

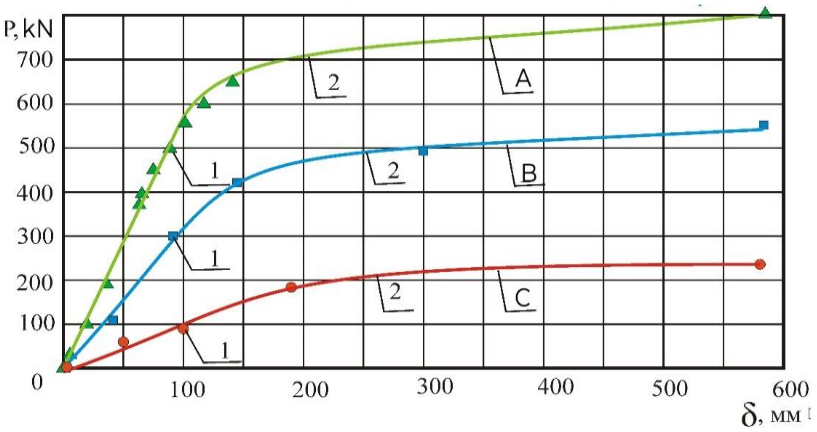


**Figure 8.** Deflection diagram δ in the middle of the lower truss girders under loading conditions: A – 20°C; B – 200°C; C – 450°C

In these and the following diagrams: 1 – experimental points, 2 – the result of linear approximation of the experimental data. The diagrams highlight the areas of elastic and plastic deformation of the lower belt for each of the temperatures considered. The diagram of maximum stresses is constructed σ in the lower belt of the truss under loading at 20°C, 200°C, and 450°C (Fig. 9).

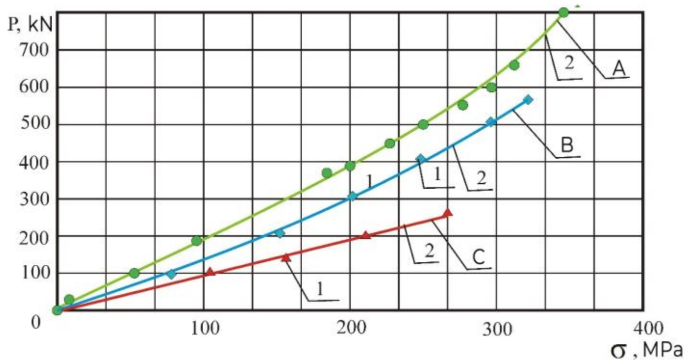


**Figure 9.** Diagram of maximum stresses σ in the lower belt of the truss under loading at conditions:
A – 20$^{O}$C; B – 200$^{O}$C; C – 450$^{O}$C

And on the basis of it, the dependence of the strength of the welded 18000x3600 truss on temperature (Fig. 10).

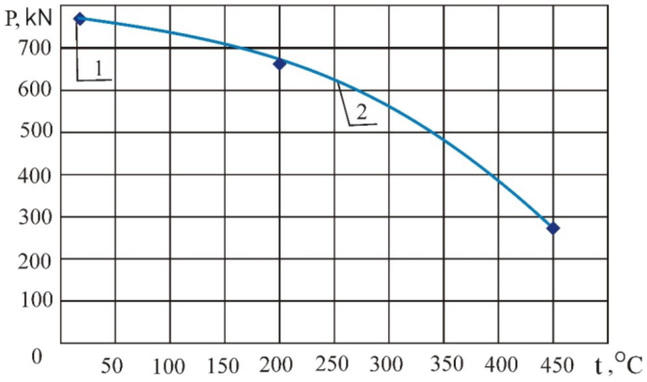


**Figure 10.** Effect of temperature on the strength of a welded truss truss 18000x3600

For the operating conditions, it will be important to know the dependence according to which the bearing capacity of a welded 18000x3600 truss changes within its deformation when the temperature rises from room temperature to fire temperature (Fig. 11). Obviously, this relationship is not linear. For practical use, it would be more convenient to use an analytical rather than a graphical dependence, which would allow predicting the maximum load on the truss at the limit of its ultimate state.

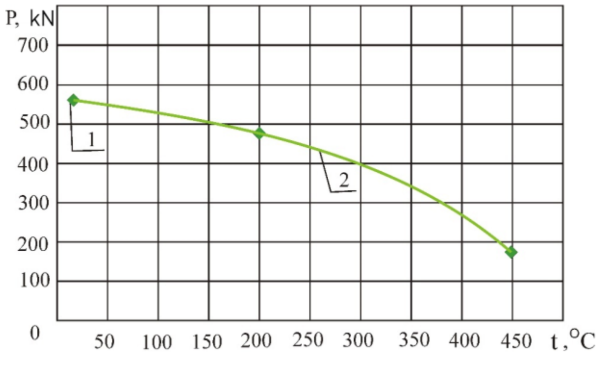


**Figure 11.** Effect of temperature on the bearing capacity of a welded 18000x3600 truss within its elastic deformation

From the point of view of predicting the operating conditions of the truss before the onset of the limit state, the most noteworthy of the obtained graphical dependencies is the effect of temperature on the bearing capacity of the welded 18000x3600 truss within its elastic deformation (Fig. 11). It is the exhaustion of elastic deformation that causes the onset of the limit for this structure. At higher loads, the plastic deformation becomes irreversible, and this, in turn, causes the loss of stability of the rods and the destruction of the truss.

When processing the modeling results according to (Fig. 11) and the general analytical description the constants A, B, and C were determined. As a result, the general dependence took on a specific form $P_{max(t)} = P_{max20}+55.25-50-1.005^{t}$, kN. Where $P_{max(t)}$ is the maximum load that the truss can withstand at a temperature t in the range from 20 to 450$^{O}$ C; $P_{max20}$ is the maximum load that the truss can withstand under force at room temperature; t is the temperature value in the range from 20 to 450$^{O}$ C for which the truss strength is determined.

The values of the maximum loads that the truss can withstand at a temperature t in the range from 20 to 450$^{O}$C, determined by dependence for discrete temperatures, are given in Table 1.

**Table 1**

Maximum loads that a truss can withstand at different temperatures and t, determined by dependence

| Temperature t,$^{O}$ C | 20 | 100 | 200 | 300 | 400 | 450 |
|---|---|---|---|---|---|---|
| Load $P_{max(t)}$, kN | 565 | 538 | 485 | 397 | 252 | 149 |

A combined graph of the results (Fig. 12) of the computer modeling experiment (Fig. 11) and analytical calculations according to dependence, summarized in Table 1, was generated.

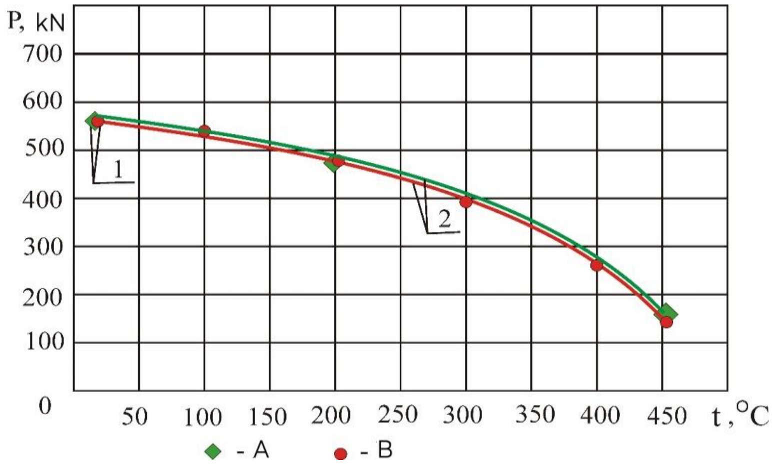


**Figure 12.** Combined graphs of the results of a computer modeling experiment (points A) and analytical calculations (points B) to determine the maximum allowable load on a welded truss under force and temperature effects: 1 – design points; 2 – linear approximation of the results

When generating combined graphs of the results of the computer modeling experiment and analytical calculations to determine the maximum allowable load on the welded truss under the action of force and temperature effects (Fig. 12), there was an almost complete coincidence of the lines. However, to visualize the process of alignment, the lines are conditionally separated by a minimum distance. When quantitatively comparing the values of $P_{max(t)}$ determined by the computer modeling experiment and the analytical calculation according to the proposed dependence, the results coincided at the level of 97.5...98.3%.

**Conclusions.** To determine the strength and deformability of a welded truss under force and temperature effects, a computer modeling experiment was performed for a full-scale truss of 18000x3600. According to the results of the experiment visual and numerical information on the stress distribution for all structural elements of the truss was obtained. It was found that the maximum stresses during the loading of the truss are localized in the lower girders, so it is its behavior that determines the behavior of the truss as a whole; Also an analytical dependence has been developed that makes it possible to determine the value of the maximum permissible load on the truss at temperatures up to 450°C from the known value of this load for room temperature conditions;

The resulting dependence should be used in the design or operation of trusses to determine the maximum permissible loads on the structure at elevated temperatures. This will allow to take into account the complex influence of high temperatures and will help in the process of designing welded trusses with optimal strength, reliability and durability in various emergency situations.

**References**

1. Rotter J., & Usmani A. Fundamental principles of structural behavior under thermal effects. Fist international workshop on structures in fire, 2000. Copenhagen.
2. Yang Y., Lin T., Leu L., & Huang C. Inelastic postbuckling response of steel trusses under thermal loadings. Journal of Constructional Steel Research. 2008. 12 p. https://doi.org/10.1016/j.jcsr.2008.01.004
3. A. H. Buchanan, A. K. Abu, Structural. Design for Fire Safety, Second edition. Wiley. 2017. https://doi.org/10.1002/9781118700402
4. D. D. Özberk, Cost Comparative Analysis of Passive Fire Protection Methods in Steel Structures Systems (MSc thesis), Pamukkale University, Science Institute Denizli Turkey. 2010.
5. Kovalchuk Ya., Shynhera N., Shved Ya. Formation of input information arrays for computer simulation of welded trusses behavior under thermal force effects. Scientific Journal of TNTU. Tern.: TNTU. 2023. Vol. 110. No. 2. P. 118–124. https://doi.org/10.33108/visnyk_tntu2023.02.118
6. DSTU 2651:2005 Stal vuglytseva zvychaynoiy yakosti. Marky GOST 380-2005. Derzspozivstandart. Ukraina, Kyiv. 2006. 56 p.
7. Shved Ya., Kovalchuk Ya., Shynhera N. Welded truss deformation under thermal influence. Scientific Journal of TNTU. Tern.: TNTU. 2022. Vol. 105. No. 1. P. 13–18. https://doi.org/10.33108/visnyk_tntu2022.01.013
8. Shynhera N. Ya. Statystychna model dlia vyznachennia zalyshkovoho resursu typovoi zvarnoi fermy pry tsyklichnykh navantazhenniakh: dys. na zdobuttia nauk. stupenia kand. tekhn. nauk: 01.05.02. Ternopil, 2012. 166 p.
9. D Lin T. J, Huang C. W. and Yang Y. B. "Inelastic Thermal Analysis of Preloaded Steel Trusses Undergoing Heating and Cooling Stages". J. Eng. Mech. 2012. 138 (5). P. 468–477. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000343
10. Haichao W., Hairong F., Zhongtao H. 2014. Study on present situation and prospect of fatigue strength and fatigue life of welded structures. Welding. No. 7. P. 26–31.

**Список використаних джерел**

1. Rotter J., & Usmani A. Fundamental principles of structural behavior under thermal effects. Fist international workshop on structures in fire. 2000. Copenhagen.
2. Yang Y., Lin T., Leu L. & Huang C. Inelastic postbuckling response of steel trusses under thermal loadings. Journal of Constructional Steel Research. 2008. 12 p. https://doi.org/10.1016/j.jcsr.2008.01.004
3. A. H. Buchanan, A. K. Abu, Structural Design for Fire Safety, Second edition. Wiley. 2017. https://doi.org/10.1002/9781118700402
4. D. D. Özberk, Cost Comparative Analysis of Passive Fire Protection Methods in Steel Structures Systems (MSc thesis), Pamukkale University, Science Institute, Denizli. Turkey. 2010
5. Ковальчук Я., Шингера Н., Швед Я. Особливості формування вхідних інформаційних масивів для комп’ютерного моделювання поведінки зварних ферм при термосилових впливах. Вісник ТНТУ. 2023. Випуск 110. № 2. С. 118–124. https://doi.org/10.33108/visnyk_tntu2023.02.118
6. ДСТУ 2651:2005. Сталь вуглецева звичайної якості. Марки. (ГОСТ 380-2005). Держспоживстандарт України, Київ, 2006. 56 с.
7. Швед Я., Ковальчук Я., Шингера Н. Деформування зварної ферми при теплових впливах. Вісник ТНТУ. 2022. Випуск 105. № 1. С. 13–18. https://doi.org/10.33108/visnyk_tntu2022.01.013
8. Шингера Н. Я. Статистична модель для визначення залишкового ресурсу типової зварної ферми при циклічних навантаженнях: дис. … канд. техн. наук: 01.05.02. Тернопіль, 2012. 166 с.

9. D Lin T. J, Huang C. W, and Yang Y. B. «Inelastic Thermal Analysis of Preloaded Steel Trusses Undergoing Heating and Cooling Stages». J. Eng. Mech. 2012. 138 (5). P. 468–477. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000343
10. Haichao W., Hairong F., Zhongtao H., 2014. Study on present situation and prospect of fatigue strength and fatigue life of welded structures.Welding, No. 7. P. 26–31.

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# АНАЛІЗ МІЦНОСТІ ТА ДЕФОРМІВНОСТІ ЗВАРНОЇ ФЕРМИ ПРИ НАВАНТАЖЕННІ В УМОВАХ ПОЖЕЖНО-АВАРІЙНОЇ ТЕМПЕРАТУРИ

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***Резюме.*** *Зварні ферми широко застосовуються в цивільному будівництві завдяки оптимальному поєднанню високої технологічності та здатності працювати в різних силових сценаріях. Такі конструкції в процесі експлуатації зазнають комплексного впливу різних технологічних та аварійних чинників. Це ускладнює визначення ключових параметрів, необхідних для безперебійної роботи ферм протягом планового періоду експлуатації. При одночасному впливі силових і високих температурних факторів на конструкцію ферми можуть виникати пошкодження в конструктивних елементах та їх з'єднаннях унаслідок зміни механічних властивостей матеріалу, які можуть призвести до руйнування конструкції. Для виявлення особливостей деформування й руйнування зварної ферми було виконано натурні експериментальні дослідження для фізичної моделі при температурному впливі в* $20^{O}C$*,* $200^{O}C$*,* $450^{O}C$*. Також було виконано комп'ютерний моделюючий експеримент для аналогічних параметрів впливу на ферму. На основі отриманих результатів натурного і комп'ютерного моделюючого експериментів згенеровано графіки деформацій, які дають можливість дослідити міцність і деформівність навантаженої зварної ферми при пожежно-аварійній температурі. Побудовано серію графічних залежностей, які характеризують міцність і деформівність ферми при її навантажуванні за різних температур. Розроблено аналітичну залежність, яка дає можливість визначити значення гранично допустимого навантаження на ферму при температурах до* $450^{O}C$ *за відомим значенням цього навантаження для умов кімнатної температури зі співпаданням результатів на рівні 97,5…98,3%. Отриману залежність (графічну чи аналітичну) доцільно використовувати при проектуванні чи експлуатації ферм для визначення максимально допустимих навантажень на конструкцію за умов підвищених температур.*

***Ключові слова****: зварна ферма, температура, металеві конструкції, тепловий вплив, температурні деформації, локальний температурний вплив, механіка руйнування.*

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