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FIRE RESISTANCE DESIGN ANALYSIS FOR STRUCTURAL CONNECTIONS ACCORDING TO EUROCODE

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Abstract. Correct assessment of fire resistance of building structures requires accurate mechanical modeling of material behavior, taking into account thermal creep in the stress-strain response of materials at elevated temperatures. Finite element models of fire-resistant structures using different types of coatings have been developed [6]. Using the example of timber nodal joints, the article presents a review of works and models of steel dowels. The review is based on experimental results presented in the literature and their application to models of nodal joints at elevated temperatures. The works considered in the review provide extensive factual material on the bearing capacity of a dowel joint and its stiffness. Today, these issues are actively studied by many researchers. A two-component model was analyzed in detail, on the basis of which a series of samples were compared under normal operating conditions and under fire conditions, and the corresponding stress coefficients for different degrees of fire exposure were obtained. The limit states of a dowel joint are the loss of strength due to plastic bending of the dowel in the socket when embedding wood. The analysis of numerical experiments makes it possible to verify the validity of the current design rules and standards [1, 2] and national design standards implemented in them [3-5], and also allows to identify shortcomings and limitations of the application of fire resistance design rules for this type of connection. The results emphasize the need to include the actual operation of dowels in the connections of wooden structures in modern advanced structural calculations for fire resistance and in engineering practice. The review considers an example of a symmetrical connection with two shear planes, the implementation of the finite element model and the results obtained. Today, the use of calculation methods for assessing fire resistance is associated with the introduction of the latest software computing complexes, in particular, such as LIRA-SAPR, Ansys Mechanical, Comsol Multi-physics, IdeaStatica and others [6, 8, 9]. New research allows us to improve information bases for creating tools for numerical modeling of complex structures in the direction of harmonizing international and national standards of Ukraine in the field of construction, taking into account the actual stiffness of timber structure nodes under temperature conditions [7, 39].

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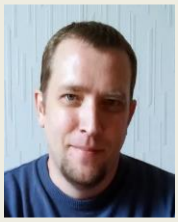

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INTRODUCTION

The progress of scientific research on the fire resistance of building structures has accelerated in recent years. This is due, not least, to the fact that fire safety is moving from regulatory [1-5] to operational solutions [6-8]. Software tools have been developed and successfully used to assess the fire resistance of steel and reinforced concrete structures. Using the "LIRA-SAPR" software (Ukraine), a method for numerically studying the fire resistance of reinforced concrete structures using non-stationary temperature fields in concrete and reinforcement, which implements the fire regime using the "Heat Conductivity" system [6], Finite element models of fire-resistant structures using various types of coatings have been developed to assess the fire resistance of structures, determine the fire resistance limit of reinforced concrete structures with changed stiffness characteristics due to the influence of elevated temperatures, as well as the temperature distribution in the nodes of the models. The library of finite element models of thermal conductivity contains one-dimensional, flat and spatial elements. Nonlinear thermal conductivity, implemented for rod, plate and volumetric finite elements, allowed us to estimate the thermal conductivity coefficient, take into account the change in material characteristics due to the influence of temperature heating in
accordance with the requirements of [3].

This ensures structural adequacy at all stages of the life cycle of the structure. The functional requirement is to ensure the necessary load-bearing capacity for a sufficient time for safe evacuation and rescue [4]. The specifics of the operation of wooden structures require further study of the characteristics of materials under the influence of fire and improvement of calculation models. One of the key features of the implementation of fire design standards based on characteristics is the assessment of the fire resistance of the structure as a whole and its nodal connections, hence the need to study the thermomechanical behavior of the material at elevated temperatures and develop material models suitable for numerical implementation [10].

For adequate modeling of the structure, the work of the connection is very important. In the case of wooden structures, they are semi-rigid, and their behavior affects the overall stress distribution, the consideration of which leads to a more realistic structural modeling.

The calculation schemes of the considered building structures are required to be as close as possible to the real structure, taking into account the peculiarities of its functioning.

Calculation models are especially complex in relation to wooden structures. They are somewhat conditional, requiring consideration of both the statistically random anisotropic physical and mechanical characteristics of materials and the nature of the operation of different materials in the contact zones.

Depending on the purpose of the calculation, both linear-elastic models and models taking into account geometric and physical nonlinearity can be considered (Fig. 1).

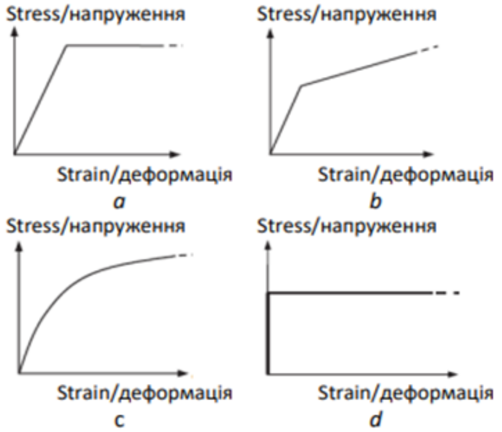

Fig. 1 Alternative stress–strain relationships commonly used in non-linear analysis:
a - elastic-perfectly plastic; b - elasto-plastic with strain hardening; c - continuously varying; d - rigid plastic behaviour

Рис.1 Альтернативні залежності напру-ження-деформації, що зазвичай використо-вуються в нелінійному аналізі: а - ідеально пружно-пластичні; б - пружно-пла-стичні з деформаційним зміцненням; в – безпе-рервно змінні; г - жорстко-пластичні

For calculations of pin-type connections, calculation with limit state analysis for fully plastic behavior of materials is mainly used.

The purpose of the article is to analyze the methods for calculating the stressed-deformed state of dowel joints of wooden structures, taking into account non-stationary temperature fields in wood and dowels for a standard fire temperature regime, which make it possible to evaluate the real operation of the connection components and the fire resistance of the joints.

The materials and methods of research consist in studying the results of experimental and theoretical research in comparison with the existing theoretical base.

The object of research is the directions, methods and experimental data obtained on the basis of the analysis of scientific sour.

PROBLEM STATEMENT AND RESEARCH ANALYSIS

For room temperature design, the modern design methodology of the Eurocode 5 design code [2] is based on the theory of plastic deformations and the results of Johansen [11] and uses the calculation of the plastic limit state to determine the bearing capacity of the connection [12, 13] (Fig. 2). Further studies are based on the theory of plastic deformations (European Yield Model EYM). With changes and adaptations, this theory is the basis of the design codes for timber structures Eurocode (EC5), similar to the content of the national design codes of the USA (NDS), Canada (CSA 086), which are developed on the basis of EYM.

Dowel joints are theoretically considered semi-rigid [14]. This takes into account the phenomenon of initial slippage, which occurs in joints with a fastener fit and continues until contact with the hole is achieved. Failure at this stage is brittle and is considered unacceptable. In contrast, viscous work (i.e., plastic with significant deformations) is characteristic of well-designed joints [15, 16, 17].

For the calculation of doweis in [2], expressions are proposed that are a function of the density of the timber and the diameter of the fastener. These expressions for the work of the dowel do not take into account some effects, such as the angle of inclination of the load to the grains or the geometry of the joint, which are fundamental for accurate modeling.

The calculation formulas are analyzed in detail by us in the review [29].

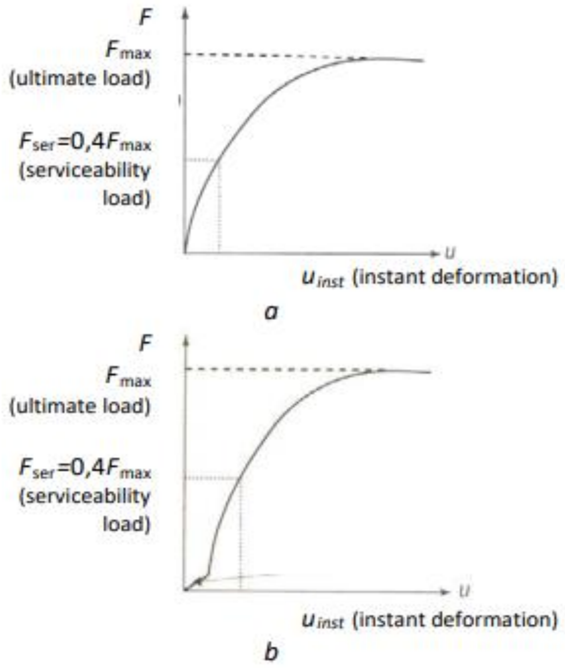

Fig. 2 Typical "load - shear deformation" relationships for dowel-type connections: a - on screws and nails; b - on bolts and dowels

Рис.2 Типові залежності "навантаження - деформація зсуву" для з'єднань нагельного типу: а - на шурупах та цвяхах; б - на болтах та нагелях

Numerical simulations of timber joints at room temperature have been carried out by many researchers [17, 18, 19]. In [20, 21, 22] the joints were modelled as three-dimensional, but it was shown that their behaviour can also be analysed using two separate two-dimensional approaches. The behaviour of the timber (perpendicular to the tongue) is actually modelled by two-dimensional finite element models [23-25], while the behaviour of the tongue (parallel to the tongue) is actually modelled by beam finite elements with elastic properties relative to the timber [13, 26, 27, 28].

Examples of finite element modeling of timber joints under fire loading are given in [29, 30] and in [29] a mechanical analysis of the joint is also performed. The conclusion made in [31] is that the influence of the number of

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fasteners on the calculation of the load-time-to-failure curves is very small. Thus, the use of a single dowel for modeling timber dowel-type joints under fire should provide accurate results.

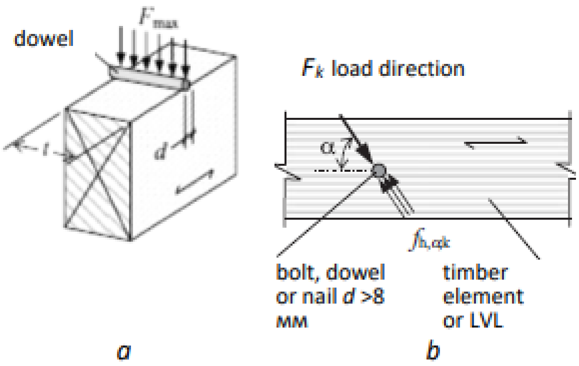

Fig. 3 Modeling the interaction of timber and dowel elements

Рис.3 Моделювання взаємодії деревини та нагеля за EC5

Wood is a consumable material. However, complete combustion of structural elements is very rare. The development of a growing layer of charcoal acts as an insulator and protects the inner core, but at the same time reduces the efficiency of the transverse surface for transferring loads.

The results of the paper [32] provide an opportunity to analyze the behavior of both timber and dowel under conditions of thermal flow. To achieve this goal, finite element simulations were performed using the specialized finite elements SAFIR [33].

The component model considers the connection as a set of individual components. Each component in the solution proposed here is modeled separately, with its own stiffness and strength. When the connection is loaded, the force distribution in the connection is determined by the relative stiffness/strength and position of the individual components [34]. For a dowel connection with a single fastener, two components can be clearly identified: the wooden element and the steel dowel.

To confirm the modeling results, the authors conducted wood crushing tests in accordance with standard requirements (Fig. 4).

Test results showing a displacement curve are given, for example, in [13, 18, 35]. When the force is applied along the fibers, the ultimate strength and initial stiffness are higher, while the stiffness after plastic deformation is lower than when the force is perpendicular to the fibers [36].

In case the required experimental test results are not available, it is acceptable to use characteristic values, since the model is used for theoretical research, and not for the analysis of a specific wood species or sample.

The materially nonlinear behavior of the dowel cross-section is described discretely using a fiber model, where the cross-section of a steel dowel is considered as a set of fibers, each of which has a one-dimensional stress-strain relationship. In [32], an elastic-ideally plastic stress-strain relationship was considered for the material model of dowels at room temperature.

The scheme proposed in the work is presented in Fig. 5 for the case of a double shear connection. A typical finite element modeling of the connection model uses a series of beam elements to discretize the dowel on an elastic support at each node according to the behavior of the timber.

In paper [32] the properties of the timber components are determined by assuming that these components are continuously distributed along the length of the dowel (the concept of a beam on an elastic base). In the finite element modeling, the strength and stiffness properties of the timber components are determined by the embedding strength.

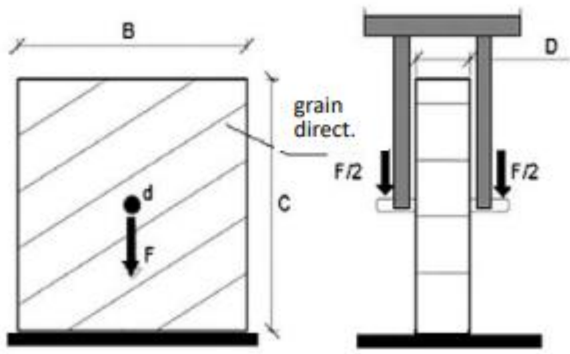

Fig. 4 Test principle to EN383

Рис.4 Схема стандартних випробувань на зминання в отворі

Strength and stiffness characteristics were obtained for the simulated specimens at room temperature and compared with the results from the Hankinson expressions for the fiber inclination in the connection [2], as well as with the experimental results from [18, 35]. The calculated force-displacement curves are mostly within the range of the experimental results. Both stiffness and strength were simulated accurately.

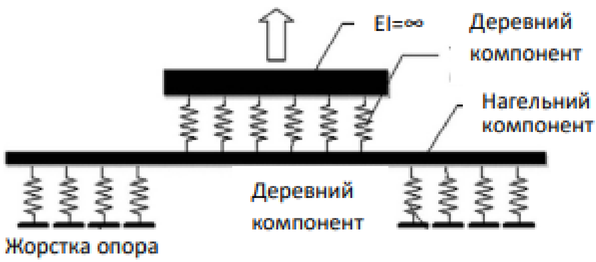

Fig. 5 Model of a single fastener connection
Рис.5 Модель однонагельного зєднання

The numerical model of the steel dowel is compared with the experimental one for a symmetric connection (double shear) [18]. The numerical results are in good agreement with the experimental results both in terms of initial stiffness and ultimate strength, both for the case of a load parallel to the fibers and for the case of a transverse member loaded perpendicular to the fibers.

In all cases, the difference between the model failure loads at plastic failure loads is less than 5%. The failure modes of the numerical model are also in agreement with the plasticity theory and Eurocode 5.

In our review, we examine in detail the model presented in [32]. It fully and exhaustively presents both the considerations regarding the node model and the results of calculations, and the obtained results are compared with the experimental ones.

The analysis of the model at elevated temperatures was performed in work [32].

The use of the component model for timber connections under fire loading is performed in a two-step approach: first, a three- dimensional thermal analysis of the connection is carried out that allows the determination of the temperature field in fasteners and timber; second, the component model previously described for the connection is used to determine the mechanical behaviour of the connection.

The three-dimensional thermal analyses of the connections were carried out with material thermal properties defined in Eurocodes [23–25] using the program SAFIR. It is assumed that timber and steel will remain connected during thermal analysis and that no gap develops at the interface.

A different finite element mesh was used for the thermal analysis. In this case, the temperature of the model components was read from the thermal model for further mechanical calculation.

The reduction in the strength and stiffness parameters in compression was taken into account by the coefficients given in Eurocode 5.

The dependences of strength and deformability for different temperatures were constructed.

The non-linear mechanical properties at elevated temperatures for the pins were obtained from the recommendations of Eurocode 3.

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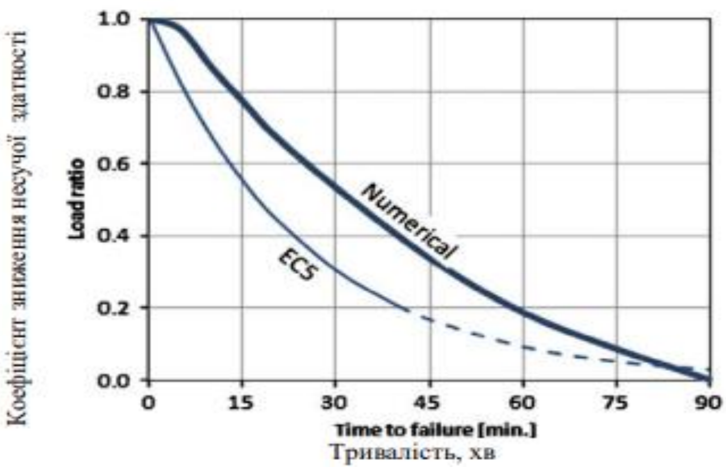

Fig. 6 Fire resistanc e for a single dowel connection [32]
Рис.6 Вогнестійкість однонагельного з’єднання [32]

Thermal analysis was performed using the finite element program SAFIR for isolated fastening using a finite element mesh. It is assumed that the connection has symmetry with respect to the axis of the dowel. The model assumes an ideal thermal contact at the interface of wood and steel, and heating is assumed to be one-sided

The temperatures along the axis of the dowel were determined at two different locations: for the steel dowel at the interface between the dowel and the wood, uniform over the entire diameter, and for the wood at a distance of 0.5d from the dowel surface.

It is important that the stiffness of the wood will depend on the temperature profile in the direction perpendicular to the dowel.

Since the temperature in the wood varies with the distance from the dowel, the spring can be considered as a series of springs with different stiffness properties. For simplicity, the model of the wood component along the dowel was used as an equivalent stiffness, i.e. a single temperature.

By calibration, it was found that a distance equal to half the diameter gives a good correlation with the experimental results.

The temperature distribution in the wood at the interface with the pin is obtained by calculation. Temperature curves are given, which are then entered into the component model, and the material properties are adapted accordingly.

After 60 minutes, the joint is still capable of withstanding 20% of its initial load-bearing capacity. The curve obtained from the model is compared with the curve of load factor versus time to failure according to Eurocode 5. The graph shows a fire resistance limit of 40 minutes. Experimental results give a longer time, but it has been shown in [31] that the Eurocode 5 model is a conservativeculation of load-time curves to failure is very small. The comparison showed the correspondence between the numerical and experimental results.

In work [31], a conclusion was made about the sufficient accuracy of approximation, so a longer time to failure can be expected.

The joint was chosen so that all failure modes typical of a timber joint in double shear can be observed: a dowel with two plastic hinges; a single hinge in the central member; and compression of the timber. The behaviour of a double shear symmetrical joint is illustrated in Fig. 7 - 9. The graphs show dotted lines that correspond to the limit of complete charring of wood at time periods. The vertical solid line corresponds to the boundary of the central and lateral elements. The graphs are plotted to the axis of symmetry. Distribution of moments along the dowel (Fig. 7).

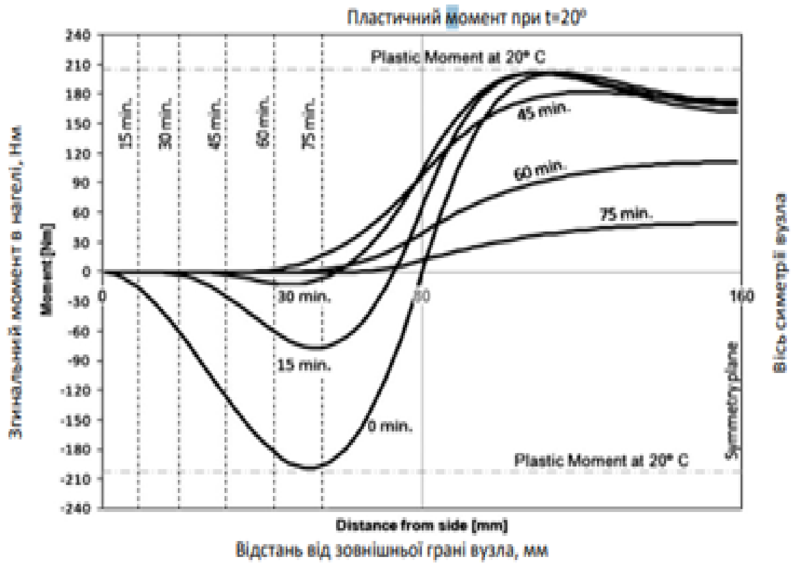

Fig. 7 Final moment diagrams in the dowel at times 0, 15, 30, 45, 60 and 75 min [32]

Рис.7 Епюри згинальниз моментів в нагелі у проміжки часу 0, 15, 30, 45 та 75 хв. [32]

At normal temperature, two hinges are fixed in the dowel. When the temperature increases, the moments are redistributed. When the moment in the lateral elements decreases, the fracture occurs in the middle element and a hinge is formed in the middle element. A decrease in the thickness of the lateral elements is observed and the fracture mode changes again. The moment in the central element decreases again, and the final fracture occurs from the crushing of the wood without the formation of a plastic hinge.

Fig. 8 shows the movement of the dowel, the location of the plastic hinge is clearly visible. The fracture of the wood in the zone of final displacements is observed. Fig. 9 show the stresses in the timber component at the corresponding time intervals. When the temperature increases above 20 degrees, the strength of the wood decreases; the plateau is not constant.

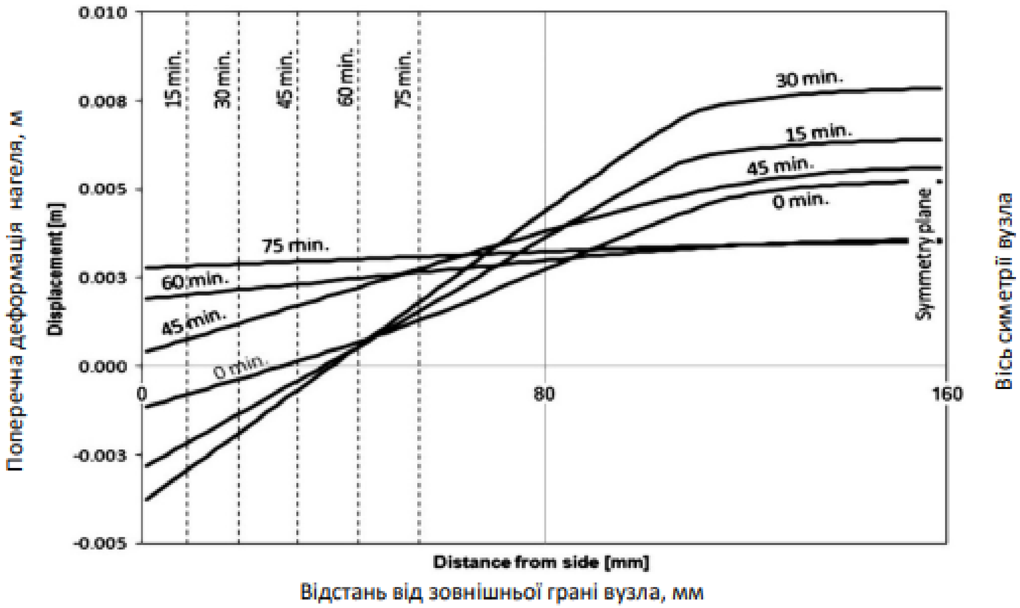

Fig. 8 Deformation of the dowel at failure at times 0, 15, 30, 45, 60 and 75 min [32]
Рис.8 Поперечна деформація нагеля у проміжки часу 0, 15, 30, 45 та 75 хв. [32]

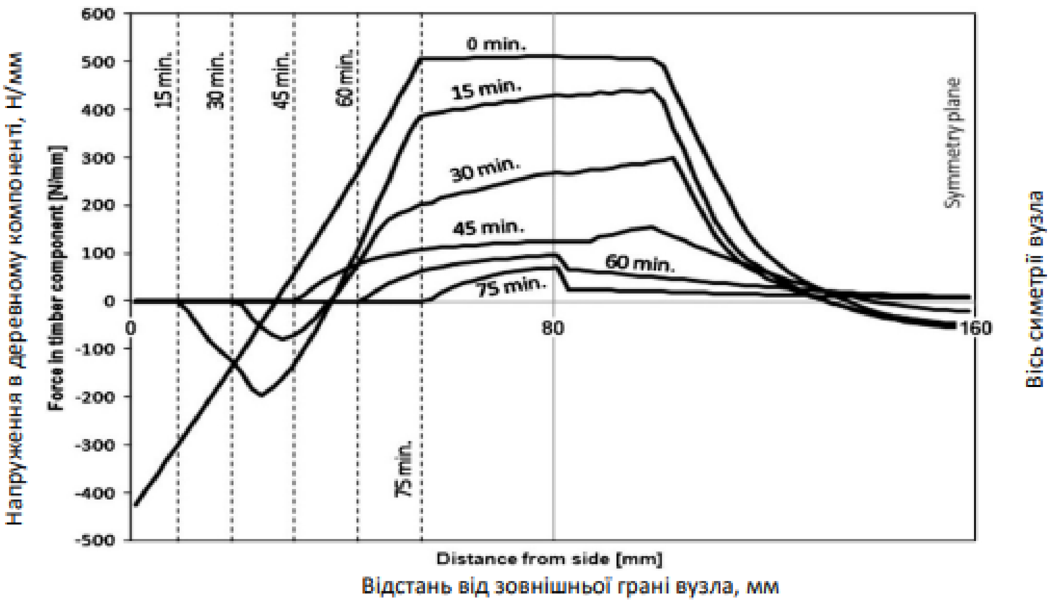

Fig. 9 Stresses at timber component at times 0, 15, 30, 45, 60 and 75 min [32]
Рис.9 Епюри напружень при зминанні деревини в отворі з’єднання у проміжки часу 0, 15, 30, 45 та 75 хв. [32]

The obtained numerical results were compared with experimental data. For this purpose, data from works [37] and [31] were used. In experimental studies on multi-nail joints, every fourth nail was made as a bolt to fix the position of the elements during fire tests.

The methodology used for fire resistance analysis was described earlier: first, a thermal analysis is performed, and then the obtained temperatures are applied to the mechanical model. Numerical modeling was performed using a single fastener, since, as noted in [31], the influence of the number of fasteners on the cal the model and the clarify the main mechanisms of the joint obtained.

The model considered is relatively simple, but at the same time validated. It provides specific values of the bearing capacity of the connection under fire exposure and fire resistance values, which are somewhat higher than those given in the standards [2] (Fig. 6).

The theoretical results and directions of experimental work presented are evidence of high research activity in the direction of improving constructive solutions and standards for designing fire resistance of structural components.

Today, the use of computational methods for assessing fire resistance is associated with the introduction and successful operation of the latest software computing complexes, in particular, such as LIRA-SAPR, Ansys Mechanical, Comsol Multi-physics, IdeaStatica [6, 8, 9] and others. New research allows improving information bases for creating tools for numerical modeling of fire resistance of nodal connections on the way to harmonizing international and national standards of Ukraine in the field of construction [7, 39] while taking into account the actual stiffness of wooden structural components under temperature conditions.

CONCLUSIONS

1. A review of publications on the study of the fire resistance of dowel-type joints was conducted. The results obtained were verified by experimental studies.
2. New models and calculation schemes were considered, which, based on classical approaches, allow for a more accurate determination of the actual stress-strain state of multi-component dowel joints.
3. The obtained research results analysed in the review allow for a refinement of approaches to the calculation of mass types of dowel joints, determination of their bearing capacity resources, and improvement of the information base for further creation of tools for numerical modelling of joint joints on the path of harmonization of international and national standards of Ukraine in the field of construction, taking into account the actual stiffness of wooden structure joints under temperature influences.

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РОЗРАХУНОК НА ВОГНЕСТІЙКІСТЬ КОНСТРУКТИВНИХ ВУЗЛОВИХ З'ЄДНАНЬ ЗА ЄВРОКОД

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Анотація. Належна оцінка структурної вогнестійкості будівельних конструкцій вимагає точного механічного моделювання роботи матеріалу з урахуванням термічної повзучості в реакції матеріалів на напруження-деформацію при підвищених температурах. Розроблені скінченно-елементні моделі вогнезахищених конструкцій із застосуванням різних типів покриттів [6]. З урахуванням особливостей деревини як конструкційного матеріалу на прикладі нагельних вузлових з'єднань представлено огляд робіт та моделей роботи вузлів.

Огляд проведено на основі наведених в літературі експериментальних результатів та їх застосування до моделей вузлових з'єднань в умовах підвищених температур. Розглядувані в огляді роботи надають великий фактичний матеріал стосовно моделей несучої спроможності з'єднання нагельного типу та його жорсткості.

На сьогодні ці питання досліджуються багатьма дослідниками. Детально аналізується двокомпонентна модель, на основі якої проведено порівняння серії зразків за нормальних умов експлуатації та в умовах пожежі, отримані відповідні коефіцієнти напружень за різного ступеню вогневого впливу. Як граничні стани нагельного з'єднання розглядаються втрата міцності через пластичний згин нагеля в нагельному гнізді при зминанні деревини стінки отвору. Аналіз чисельних експериментів надає можливість переконатися в надійності чинних правил і норм проектування [1, 2] та імплементованих до них національних норм проектування [3-5], а також дозволяє виявити недоліки та межі застосування правил проектування вогнестійкості стосовно цього виду з'єднання. Результати підкреслюють необхідність включення дійсної роботи нагелів у з'єднаннях дерев'яних конструкцій до сучасних удосконалених структурних розрахунків на вогнестійкість та в інженерну практику. В огляді розглядається приклад симетричного з'єднання з двома площинами зсуву, реалізація скінченно-елементної моделі та отримані результати. На сьогодні застосування розрахункових методів оцінки вогнестійкості пов'язане із впровадженням новітніх програмних обчислювальних комплексів, зокрема таких як Ліра-САПР, Ansys Mechanical, Comsol Multi-physics, IdeaStatica та інші [6, 8, 9]. Нові дослідження дозволяють вдосконалити інформаційні бази для створення інструментів чисельного моделювання складних споруд на шляху гармонізації міжнародних і національних стандартів України в галузі будівництва при урахуванні дійсної жорсткості вузлів дерев'яних конструкцій в умовах температурних впливів.

Ключові слова: вузли будівельних конструкцій, нагельні з'єднання, вогнестійкість, Єврокод 2, Єврокод 5.

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