МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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THE RESEARCH OF THE DEFLECTED MODE FOR THE STEEL TRUSS BRIDGE SPAN WITH UPPER-LEVEL TRAFFIC BY THE COMPUTER MODELING METHOD

Purpose. To confirm the result of bridge span classification by using the computer modelling for truss span with upper-level traffic and polygonal lover belt and to determine minimal sufficient complexity of computational model that provides a possibility of adequate numerical calculation of given structure. **Methodology.** The result confirmation was executed by the comparison of stresses, that were yielded as a result of truss' model loading with loads of predetermined class, with allowed stresses that were adopted for the determination of the afore-mentioned loading. The determination of optimal computational model was performed by the comparison of calculation results for models of different complexities. **Findings.** The results of the span modelling are similar enough to the results of it's calculation, which confirms the accuracy of both methods and provides obvious idea about work of truss elements and critical places. The comparison of calculation results of different models showed that the using of shaft model with hard junctions and elements' bending accounting is optimal. **Originality.** Computer modeling was used to confirm the results of span classification, which was conducted by the standard method. An optimal computational model was determined for trusses that are similar to given. **Practical value.** Results of analytical calculation were confirmed with demonstration of critical elements and obvious demonstration of results. The optimization of the model allows to lower calculation time and complexity of executing them for similar trusses.

Keywords: truss; classification; finite element method; FEM; modeling; optimization

Introduction

For the bridges, that were designed according to old design standards and are operated for a big period of time, the bearing capacity should be regularly be checked for the reasons of prevention of accident due to the increasing of loads and operational conditions changes. For such structures the actual bearing capacity is being determined considering the flaws and damages that have occurred during operation period. The bearing capacity of steel railway bridges in Ukraine is being determined by the classification method according to GSTU 23.6.03.111-2002 [1]

In 2015 the survey of single-track railway steel bridge that was designed according to standards of 1886, that is still being operated, was performed by the engineers of Industrial research laboratory of artificial structures of Dnipropetrovsk national university of railway transport named after academician V. Lazaryan.

Based on the survey results the classification of spans was provided, of span 0-1 in particular. The span is represented by metal truss with upper-level traffic and parabolic lower belt. The grid type is triangular with additional struts. Trusses are combined with the system of lengthwise and lateral bonds into single spatially permanent structure. The full length of span 0-1 is 46,05 meters; rated span is 44,66 meters (Fig. 1).

Fig. 1. General view of truss

Truss belts have T-shaped cross-section. Lengthwise bonds and struts have X-shaped cross-section, except strut L3-U4, which has T-shaped cross-section. Lengthwise bonds are installed in the belt's plane and lateral ones are installed in struts' plane.

The bridge was put into operation in 1903. The spans were manufactured in 1902 with the cast iron. The bridge was damaged in 1944. Span 0-1 and it's support were renewed in 1952.

The feature of span's design is the absence of gusset plate on the elements of upper belt, so that slanted struts are attached directly to the vertical plate of T-shaped cross-section of the belt. In places of strut's attachment the inserted gussets are installed. Upper belt junctions are located outside of truss joints and are enhanced with joint patches. Struts are attached to the belts and gusset plates with double-shear rivets.

Truss lower belt has polygonal shape and is joined with path gusset plates of sheet metal. It is attached to the joint gussets with the double-shear rivets.

Purpose

Based on the results of classification by standard analytical method according to GSTU 32.6.03.111-2002 [1] the decision was made to conduct numerical analysis of the span by its modeling with purpose of confirmation of classification results and creating the purpose of evident demonstration of deflected mode of the span and its critical elements.

For the numerical computation the finite-element method was chosen. The model implementation was executed using "Lira" software complex. But on this stage some questions have arisen about computational scheme development, that are based on following facts:

- On areas near the bearing axis the crossections to length ratio is quite big for the elements (Fig. 2);
- Following the aforementioned fact we will get some elements that can be modeled only as plates;
- For small enough elements, we cannot accept the hypothesis of hinges in truss joints.

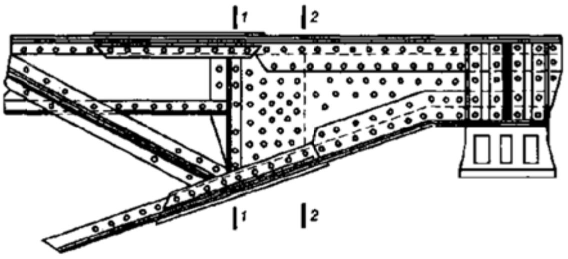


Fig. 2. Truss area near the support

Modern FEM software allow to perform the calculations with almost infinite accuracy, but, obviously, with increasing model complexity computer and human resources needed for performing a calculation will increase exponentially. So the decision was made not to create very detailed model, but to find such a complexity that while retaining sufficient precision would spend minimal time and recourses on computation.

So the purpose of the work consists of two parts:

- Sing optimal computational model for the truss;
- Perform the verification of classification results for the span.

Methodology

Modeling methods. Finding the model of optimal complexity was performed through the comparison of some models with gradual increasing of detailing level:

1. Plane bar model with hinge joints – standard way of truss computations that gives the possibility to get accurate enough results for most of grid structures;
2. Plane bar model with accounted bending work for elements – by introduction of rigid bonds in truss joints;
3. Plane system with combined plate and bar elements;
4. Spatial scheme with combined plate and bar elements.

First model was used to build influence lines for the span classification. All the elements except near support areas were represented as bars that can bear axial loads. Elements' stiffness were represented parametrically (FE №1 in "Lira" software). Near-support areas were represented as plate elements for all models because of quite big height to length ratio with leads to inexpediency and inaccuracy of representing given area with small enough quantity of bar elements (Fig. 3).

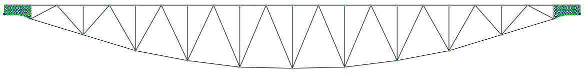


Fig. 3. Computation model for bar schemes

The second model has geometry scheme identical to the first. Stiffness of elements were again represented parametrically (FE № 2 in “Lira” software). The difference lies in allowance for the bars to bend and in bending moment transfer through joins (application of rigid joints). The change of model by including bending was conditioned by the truss design and, firstly, L1-U3 strut (see Fig. 2, Purpose). As the picture shows, the free length of the strut in quite small. Moreover, it has quite small compression stiffness together with very large bending stiffness of upper belt element (U1-U3). All of the abovementioned reasons let us recon that the upper belt element receives part of the loading through the bending.

The utilization of the third model is caused by the design of truss belts. Its elements have T-shaped cross-section with quite large height of vertical plate (Fig. 4).

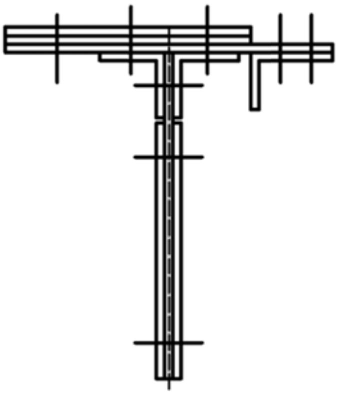


Fig. 4. Cross-section of upper belt element: the height of vertical plate is 500 mm.

Based on the abovementioned assumptions we can suppose that such a design can influence the work of both struts and belt elements because of free length reduction and partial reception of loads due to elements’ bending work.

Model was created with the combination of plate and bar elements not only in near-support areas but also on the whole length of upper and lower belts. For belt elements vertical sheets were modeled directly as plated of needed thickness and horizontal sheets – with bar elements with equivalent stiffness assigned parametrically so, that total stiffnesses of plate and bar were equivalent to the belt element’s stiffness.

The next model is, in fact, the spatial application of previous problem. Two main trusses that were designed as described before were modeled for it. Given trusses were bonded with lateral elements according to original truss design. For all the bonds bar elements with parametrical stiffnesses were used (Fig. 5).

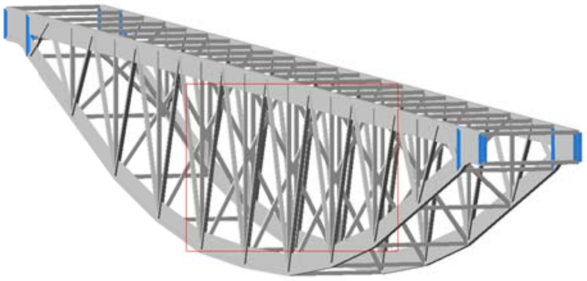


Fig. 5. Spatial truss’ model. Consists of two bonded plane models

Further the comparison of results was conducted for all four computational schemes and the optimal one was chosen.

The calculation verification method. Usually when talking about the work connected to the design, the problem is being solved that consists of determination of minimal needed cross-section for the element and is based on the data that includes loads on structure end material properties. Also, from the material and element properties and the check has place that includes the comparison of element’s bearing capacity and stresses that are caused by external loads.

$$\frac{N}{A}+\frac{M}{W}\leq R .$$

At the same time, classification method that was used for the span calculation implies the solution of problem vice versa. Having such input data as geometrical parameters of the span and material properties we need to find element’s bearing capacity (according to GSTU 32.6.03.111-2002 the bearing capacity is calculated as maximum allowed equivalent load and is then expressed as a class through the reference equivalent load.

$$k = \frac{1}{\Omega_v}\left(R \cdot G - p \cdot \Omega_p\right).$$

Unfortunately, Lira software, which was used for influence lines calculation for the span calculation, doesn't let us conduct such a computation directly. So the calculation verification or refutation can't be performed through the direct comparison of the results. Instead of it the following algorithm was used for the verification:

a) To choose an element, which class we need to verify;

b) For it to choose equivalent distributed load, that was yielded as an allowable temporal load by the classification method;

c) To load the truss model with given intensity thus modeling maximum moving load for the element;

d) To perform a numerical model calculation;

e) To look for stresses in the element, which needs the result verification.

The verification of calculation results is conducted by comparison of stresses that arise in truss element with material strength, which was accepted for element classification. I.e. if the stress in the element equals it's material strength, then the applied load is actually maximum transient load for given element.

In fact thus we solve the problem of stress determination in the element based on data that was yielded using maximum allowed stress.

The shortcoming of this method is that for each element unique loading must be created. Even for elements with the same classes equivalent loads will differ depending on influence line parameters.

Findings

For computational models comparison the influence lines were built. For the apparency of results representation let's consider influence lines for upper and lower belt elements and also for shortest and longest struts (Fig. 6 and 7).

Comparing influence lines we can see following differences:

1. Only for the first model influence lines have straight contours. Obviously, this can be explained by the absence of elements' bending work;
2. Form and ordinates of influence lines yielded by third and fourth models are almost identical (Fig. 8 and 9);

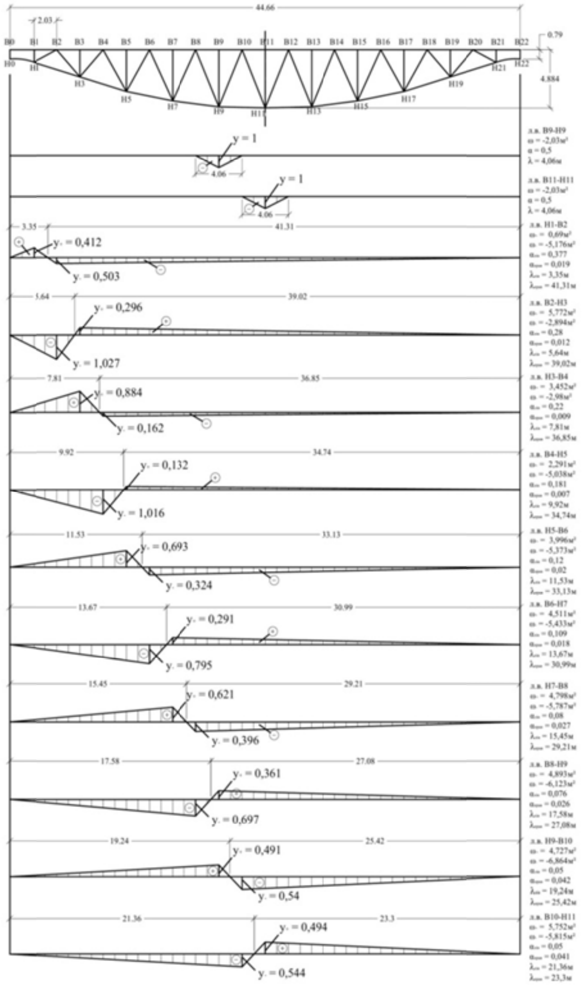


Fig. 6. Influence lines for struts by first model

3. Form and ordinates of second and third model influence lines differ by negligible values. Thus of the last three models the bar one with bending work accounting is enough for truss calculation.
4. Computations results for first and second bar models visibly differ one from another. Ordinates of lengthwise forces for the second model for belts are lower than first model ordinates by values up to 10 %, but within the panel nonzero values of moment influence lines appear;
5. For the long enough struts the difference between first and second model is negligible;
6. For small enough struts (firstly L1-U2) influence line ordinates may differ by quite large value – two times and more;
7. Stresses in vertical struts for the second model are up to three times lower than for the first one. Obviously, it is due to bending work of upper belt.

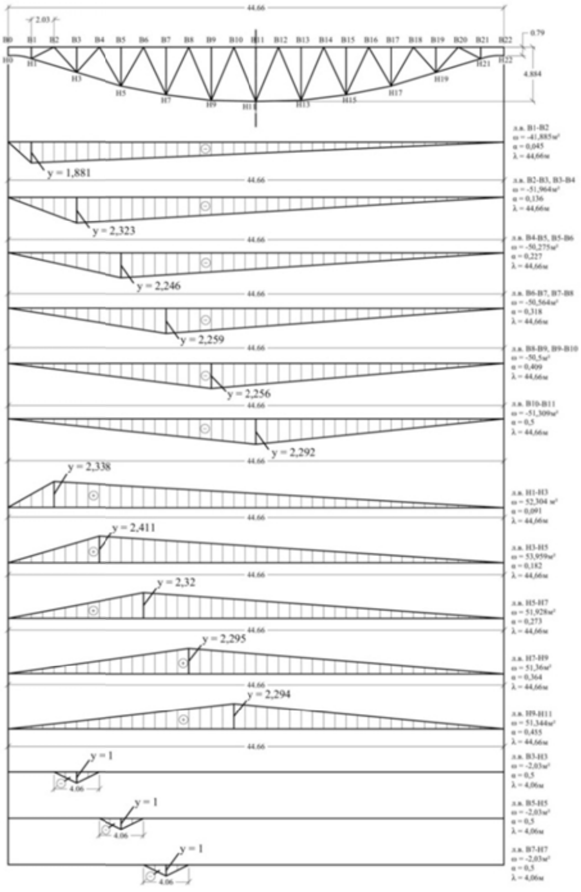


Fig. 7. Influence lines for belt elements by first model

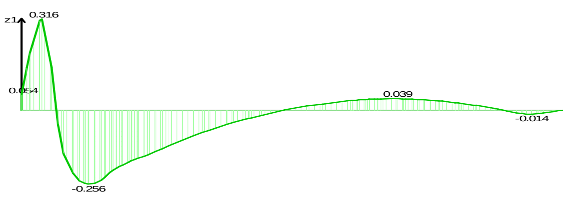


Fig. 8. Influence lines for strut L1-U3 by third and fourth model

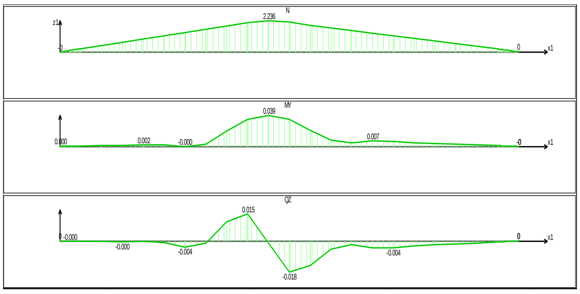


Fig. 9. Influence lines for element U8-U11 by third and fourth model

Thus the modeling results imply that the bar model with bending work accounting is optimal by the complexity and accuracy for trusses with rigid joints.

Moreover while verifying the classification results that were acquired using regular bar model it's necessary to pay attention to the bending moments in belt elements. Also the classification results of struts may have been lowered. But, because according to classification results these elements are not critical, belt elements must be revised primarily (element L3-L5 is critical one).

For verification of classification and modeling results using the abovementioned method stresses in elements were calculated by two models – bar one with accounting of bending work and spatial model that combines bar and plate elements.

Thus for element L3-L5 is 5,31 which corresponds to distributed equivalent load of 85,64 kN/m (dynamic and reliability indexes included). Besides temporal load the dead loads of truss (is calculated automatically by the software) and bridge deck (assumed to be 22,6 kN/m) was applied.

When calculating the spatial model we have the possibility to yield stress magnitudes in elements' points directly, which allows skipping all the calculations after modeling and shows graphically the deflected mode of the span. Fig. 10 shows, that in every case of distributed load the most stressed element is actually L3-L5. On Fig. 11 the truss fragment, which was calculated, is shown with contour plots of stresses as computation results. Given fragment distinctly shows that element is actually of interest for given calculation. Obviously, its stresses reach up to 171 MPa.

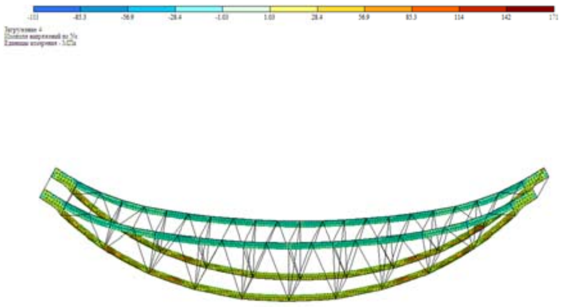


Fig. 10. General view of deformed beam with stresses' contour plots

Thus the difference between classification method and spatial modeling method turns out to be (185…171)/185=7,6 %, which is acceptable.

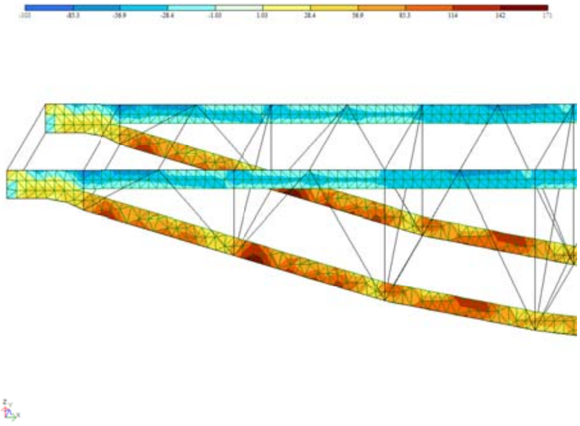
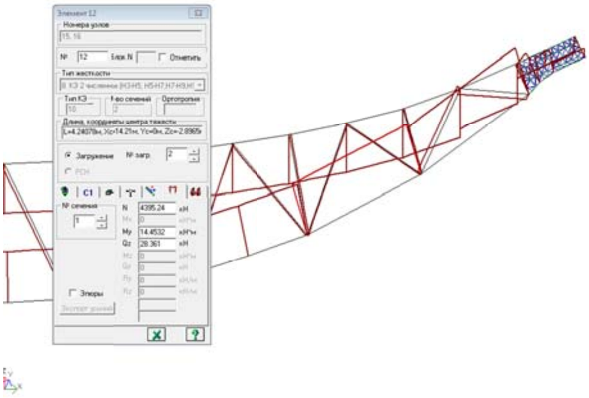


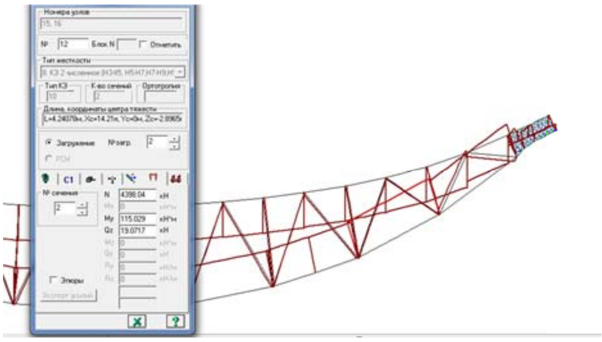
Fig. 11. Truss fragment for element L3-L5 with stress contour plots

Based on modeling results for bar scheme with analogous loads longitudal forces in the elements were yielded that were then used to obtain stress values. Fig. 12 and 13 show fragments with elements L3-L5 and information about it in two points (beginning and end of the element).



Элемент 12
Номера узлов: 15, 16
№ 12
Тип КЭ: 10
К-во сечений: 2
Длина, координаты центра тяжести: L=4.24079м, Xc=14.21м, Yc=0м, Zc=-2.8965
Загружение, № загр.: 2
№ сечения: 1
N: 4395.24 кН
Mx: 0
My: 14.4532 кН*м
Qz: 28.361 кН
Mz: 0
Qy: 0

Fig. 12. Info for the beginning point of L3-L5 element



Номера узлов: 15, 16
№ 12
Тип КЭ: 10
К-во сечений: 2
Длина, координаты центра тяжести: L=4.24079м, Xc=14.21м, Yc=0м, Zc=-2.8965
Загружение, № загр.: 2
№ сечения: 2
N: 4398.04 кН
Mx: 0
My: 115.029 кН*м
Qz: 19.0717 кН
Mz: 0
Qy: 0

Fig. 13. Info for the ending point of L3-L5 element

Calculating stresses for the first point: from the longitudal force we yield:

$$\sigma = \frac{N}{A} = \frac{4395}{264} = 16,65\ \text{kN/cm}^2 \text{ or } 166,5\ \text{MPa.}$$

Stresses from the bending moment in the stretched edge

$$\sigma = \frac{M \cdot y}{I} = \frac{1445 \cdot 8,397}{51544,5} = 0,235\ \text{kN/cm}^2$$

or 3,35 MPa.

Shear stress

$$\tau = \frac{Q \cdot S}{b \cdot I} = \frac{28,36 \cdot 1346,05}{3,84 \cdot 51544,5} = 0,193\ \text{kN/cm}^2$$

or 1,93 MPa.

Total stress from longitudal force and moment

$$\sigma = 166,5 + 2,35 = 168,85\ \text{MPa.}$$

Total overall stress

$$\sigma_0 = \sqrt{168,85^2 + 3 \cdot 1,93^2} = 168,9\ \text{MPa.}$$

Here we have the deviation with classification of 8,7 %, which is still allowable.

For the second point: from the longitudal force

$$\sigma = \frac{N}{A} = \frac{4398}{264} = 16,66\ \text{kN/cm}^2 \text{ or } 166,6\ \text{MPa.}$$

Stresses from the bending moment in the stretched edge

$$\sigma = \frac{M \cdot y}{I} = \frac{11502,9 \cdot 8,397}{51544,5} = 1,874\ \text{kN/cm}^2$$

or 18,74 MPa.

Shear stress

$$\tau = \frac{Q \cdot S}{b \cdot I} = \frac{19,07 \cdot 1346,05}{3,84 \cdot 51544,5} = 0,130\ \text{kN/cm}^2$$

or 1,30 MPa.

Total stress from longitudal force and moment

$$\sigma = 166,5 + 18,74 = 185,34\ \text{MPa.}$$

Total overall stress

$$\sigma_0 = \sqrt{185,34^2 + 3 \cdot 1,30^2} = 185,35\ \text{MPa.}$$

Which is almost identical to the rated stress value of 185 MPa.

Originality and practical value

Optimal by complexity and accuracy calculating model for truss spans with rigid joints and large bending stiffness of elements was found. Furthermore this will allow to yield accurate enough results of calculation for analogous spans without using excessive computer time and labour.

Numerical calculation was used to verify the results of its classification and visual indication of critical elements. Using of this method further lets us provide estimating calculations of spans and results verifying, both direct and reverse with less labor.

Conclusions

Based on the results of bearing capacity determination of steel span of old standards by classification method and following application of finite-element modeling that were published in this work the following conclusions can be drawn:

1. By using numeral calculation of the span by FEM its calculation results by the classification method were verified and for an element L3-L5 it was verified as critical one.
2. Applying the computer modeling for the research of deflected mode of bridges under the load that actually revolves on the stage of bridge operation allows to draw visual state of critical deflections and stresses in the elements and to make a decision about its bearing capacity renewal in time.

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ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ МЕТАЛЕВОЇ ПРОГОНОВОЇ БУДОВИ ІЗ НАСКРІЗНИМИ ФЕРМАМИ З ЇЗДОЮ ПОВЕРХУ МЕТОДОМ КОМП’ЮТЕРНОГО МОДЕЛЮВАННЯ

Мета. За допомогою комп’ютерного моделювання підтвердити результати класифікації прогонової будови мосту у вигляді ферми з їздою верхом з полігональним нижнім поясом і визначити мінімальну достатню складність розрахункової моделі для можливості адекватного чисельного розрахунку даної конструкції. **Методика.** Підтвердження результатів виконувалось за допомогою порівняння напружень, що були отримані в результаті завантаження моделі ферми навантаженням визначеного попередньо класу з допустимими напруженнями, які і були прийняті для визначення вищевказаного навантаження. Знаходження оптимальної моделі ферми було виконано порівнянням результатів розрахунку для моделей різної складності. **Результати.** Результати моделювання прогонової споруди достатньо точно співпадають з результатами її розрахунку, що свідчить про вірність обох методів і дає наочне уявлення про роботу елементів ферми а також критичні місця. Порівняння результатів розрахунку на різних моделях показало, що оптимальним є використання стержневої моделі з жорсткими вузлами і урахуванням роботи елементів на згин. **Наукова новизна.** Було використано комп’ютерне моделювання для підтвердження результатів класифікації прогонової споруди, що було виконано стандартним розрахунком. Для ферм аналогічних конструкцій встановлено оптимальну складність розрахункової моделі. **Практична значимість.** Було підтверджено результати аналітичного розрахунку прогонової споруди і показано критичні її елементи з наочною демонстрацією результатів. Оптимізація моделі дозволяє зменшити комп’ютерний час і складність виконання розрахунків для ферм аналогічної конструкції.

Ключові слова: ферма; класифікація; метод скінчених елементів; МСЕ; моделювання; оптимізація

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МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

ИССЛЕДОВАНИЕ НАПРЯЖЁННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ МЕТАЛЛИЧЕСКОГО ПРОЛЁТНОГО СТРОЕНИЯ СО СКВОЗНЫМИ ФЕРМАМИ С ЕЗДОЙ ПОВЕРХУ МЕТОДОМ КОМПЬЮТЕНОГО МОДЕЛИРОВАНИЯ

Цель. С помощью компьютерного моделирования подтвердить результаты классификации пролётного строения моста в виде фермы с ездой поверху с полигональным нижним поясом и определить минимальную достаточную сложность расчётной модели для возможности адекватного количественного расчёта данной конструкции. **Методика.** Подтверждение результатов было выполнено с помощью сравнения напряжений, которые были получены в результате загрузки модели фермы нагрузкой ранее определённого класса с допустимым напряжением, которое было принято для определения вышеуказанной нагрузки. Нахождение оптимальной модели фермы было выполнено сравнением результатов расчёта для моделей разной сложности. **Результаты.** Результаты моделирования пролётного строения достаточно точно совпадают с результатами её расчёта, что говорит о правильности обоих методов и даёт очевидное представление о работе элементов фермы и её критических местах. Сравнение результатов расчёта разных моделей показало, что оптимальным является использования стержневой модели с жёсткими узлами и учетом работы элементов на изгиб. **Научная новизна.** Было использовано компьютерное моделирование для подтверждения результатов классификации пролётного строения, выполненной стандартным расчётом. Для ферм аналогичной конструкции определена оптимальная сложность расчётной модели. **Практическая значимость.** Были подтверждены результаты аналитического расчёта пролётного строения и показаны его критические элементы с наглядным представлением результатов. Оптимизация модели позволяет уменьшить компьютерное время и сложность выполнения расчётов для ферм аналогичных конструкций.

Ключевые слова: ферма; классификация; метод конечных элементов; МКЭ; моделирование; оптимизация

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