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G. Kozbur,
O. Shkodzinsky, PhD, Assoc. Prof.,
O. Hlado
Ternopil Ivan Puluj National Technical University, 56 Ruska Str., Ternopil, Ukraine, 46001; e-mail: kozbur.galina@gmail.com

METHODS OF CONSTRUCTION OF THE GENERALIZED HARDENING CURVE

Г.В. Козбур, О.К. Шкодзінський, О.Ю. Гладьо. **Методика побудови узагальненої кривої зміцнення**. Розробка нових конструкційних матеріалів та зростаючі вимоги до ефективності та безпеки експлуатації конструкцій, і разом з тим, зменшення їх матеріалоємності посилюють вимоги до точності експериментальної та розрахункової частин дослідження. Експериментальна реалізація всього спектру напружено-деформованих станів зразків конструкційних елементів вимагає руйнування великої кількості зразків, створення і утримання вартісного обладнання. Тому пошук ефективних методів розрахунку прогнозних значень критичних навантажень для елементів конструкцій та визначення реалістичного коефіцієнта запасу є актуальною задачею. Напруження та деформації впродовж усього процесу навантаження матеріалу відслідковують за кривими деформування. У даному дослідженні увагу приділено ділянці зміцнення кривої деформування, яка відображає пластичне деформування матеріалу після досягнення межі плинності. Криві деформування в головних напруженнях та головних деформаціях є первинними для подальшої обробки та аналізу. Метою роботи є запропонувати універсальну методику отримання моделі ділянки зміцнення узагальненої кривої деформування для пластичних металевих матеріалів, яка б найкраще узгоджувалась з даними експерименту для кожного конкретного матеріалу. З цією метою введено еквівалентні напруження і деформації, які є узагальненням двох «класичних» підходів Мізеса і Треска. Модель містить єдиний параметр *p*, який визначається за результатами кількох найпростіших дослідів. Для знаходження оптимального значення *p* використовуються статистичне оцінювання якості та помилок. Застосування методики для пластичних матеріалів дозволить із задовільною точністю описувати узагальнену криву деформування та прогнозувати напружено-деформований стан матеріалу за різних співвідношень головних напружень. У комплексі з методиками врахування геометрії конструкцій отриману узагальнену криву можна використовувати для прогнозування значень реальних напружень, що виникають елементах конструкцій під навантаженням.
Ключові слова: узагальнена деформаційна крива, деформаційне зміцнення, еквівалентні напруження і деформації

G. Kozbur, O. Shkodzinsky, O. Hlado. **Methods of construction of the generalized hardening curve.** The development of new structural materials and increasing requirements for the efficiency and safety of operation of structures and at the same time, reducing their material consumption, tighten the requirements for the accuracy of the experimental and calculated parts of the study. The experimental implementation of the entire spectrum of stress-strain states of samples of structural elements requires the destruction of a large number of samples, the creation and maintenance of cost equipment. Therefore, the search for effective methods for calculating the predicted critical loads for structural elements and determining a realistic safety factor is an urgent task. Stresses and strains throughout the process of loading the material are monitored by deformation curves. In this study attention is paid to the area of hardening of the deformation curve, which reflects the plastic deformation of the material after reaching the yield strength. The stress strain curves in principal stresses and principal strains are primary for further processing and analysis. The aim of the work is to propose an universal method for obtaining a model of the hardening section of a generalized deformation curve for plastic metal materials, which would be better consistent with the experimental data for each specific material. To this end, equivalent stresses and strains are introduced, which are a generalization of the two “classical” approaches of von Mises and Tresca. The model contains a single parameter *p*, which is determined by the results of several simple experiments. To find the optimal value of *p*, statistical estimation of quality and errors is used. Application of the method for plastic materials will allow satisfactory accuracy to describe the generalized deformation curve and to predict the stress-strain state of the material at various ratios of principal stresses. In combination with the methods of taking into account the geometry of structures, the obtained generalized curve can be used to predict the values of real stresses arising by structural elements under load.
Keywords: generalized deformation curve, strain hardening, equivalent stresses and strains

1. Introduction

Prediction of ultimate stresses and strains in the material is carried out by approximating the experimental data by deformation curves or yield locus. The development of new structural materials and the growing demands on the efficiency and safety of the operation of structures, and, at the same time,

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the reduction of their material consumption increase the requirements for the accuracy of the experimental and computational parts. Experimental implementation of the full range of stress-strain states of structural elements samples requires the destruction of a large number of samples, the creation and maintenance of costly equipment. Therefore, the search for effective methods for calculating the predicted values of critical loads for structural elements and determining a realistic factor of safety is an actual task. To increase the accuracy and reliability of predictive values is possible through the improvement of methods of calculation and application of computer technology.

2. Analysis of recent research

The resistance of the material to plastic deformation and fracture is determined from the simplest experiments. Implementing a plane stress state and measuring changes in the size of the samples, we obtain pairs of values of "stress-strain", which are then approximated by the curves of the limit states in the space of principal stresses or deformation curves. In contrast to yield locus, stress-strain curves track stresses and strains throughout the loading process. Deformation curves in principal stresses and principal deformations are primary for further processing and analysis. In this study, attention is focused on the area of deformation strengthening of the deformation curve, because the scientific interest is the behavior of loaded structures, for which plastic deformation is allowed. In this case, the stress is called critical, at the excess of which local plastic deformations develop in the sample.

The question of constructing the deformation curve of metallic materials for the area of large deformations depending on the shape of the sample is considered in [1]. A review of existing modern methods for constructing the deformation curve of metallic materials for the area of large plastic deformations was carried out in [2]. In [3], a generalized approximation model for the deformation curve of metallic materials is proposed, which takes into account all stages of deformation. Review and analysis of different approaches to the construction of a single curve is described in [4], [5]. In [6], a review and comparative analysis of approximation models of the generalized deformation curve was performed. However, the coverage in the literature of the prediction of the stress-strain state of materials in the field of large plastic deformations is not sufficient. It is still difficult to find generalized deformation curves for plastic metallic materials, which can be used to predict large uniform plastic deformations at different types of complex stress state.

3. The purpose and objectives of the study

For predicting and engineering calculations of complex stress states, hypotheses are used that allow to replace the complex stress state with its equivalent uniaxial stress state. According to the "single curve" hypothesis, it is possible to select such equivalent coordinates in which the deformation curve will be invariant with respect to the type of applied load [7].

Most often, the maximum shear stresses $\tau_{\max}$ and maximum angular deformations $\gamma_{\max}$ or stress intensity σ_i and intensity of deformations ε_i (or octahedral coordinates proportional to them) are used as equivalent coordinates to construct the material deformation curve. These two "classical" approaches to the construction of generalized deformation curves are based on two classical theories – the Tresca theory of largest shear stresses and von Mises energy theory. However, for most materials the deformation curve constructed at maximum shear stresses or stress intensities depends on both the load trajectory and the ratio of principal stresses at proportional loading. In [8], it was proposed to describe a single deformation curve through the introduction of a weighted average stresses and strains calculated by two "classical" approaches. The authors in [9] proposed another method of averaging, which is better consistent with the energy approach of Mises. A fairly complete overview of approaches to the introduction of equivalent coordinates is given in [5]. Experimental data show that for some metallic materials there is a better agreement with one of the "classic" generalized curves, for the other part – with new ones that use one or another form of averaging. Therefore, **the purpose of the work** is:

– to propose a universal method for constructing a generalized hardening curve for plastic materials, which would be consistent with the classical ones and take into account the deviations from them of experimental data for the class of plastic isotropic metallic materials;

– describe the procedure for finding the material constant to build a model of the generalized deformation curve.

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4. Method of construction of the generalized strengthening curve

4.1. Mathematical model of the generalized deformation curve

To obtain a universal in this sense analytical description of a single, invariant with respect to the type of stress state deformation curve it was proposed [10] to generalize both classical approaches and introduce equivalent coordinates in the form (1), (2).

$$\sigma_{eq} = \frac{p}{2}\left[\frac{|\sigma_1-\sigma_2|^p + |\sigma_2-\sigma_3|^p + |\sigma_1-\sigma_3|^p}{2}\right]^{\frac{1}{p}}, \quad (1)$$

$$\varepsilon_{eq} = \frac{p}{2(p+1)}\left[\frac{|\varepsilon_1-\varepsilon_2|^p + |\varepsilon_2-\varepsilon_3|^p + |\varepsilon_1-\varepsilon_3|^p}{1/2}\right]^{\frac{1}{p}}, \quad (2)$$

where σ_{eq} – equivalent stress;

ε_{eq} – equivalent deformations;

p – some positive number.

The proposed model contains the parameter *p*, which reflects the degree of deviation of the properties of the real structural material from the properties of the idealized material, for which you can get a single deformation curve in the coordinates $\tau_{\max}-\gamma_{\max}$ or $\sigma_i-\varepsilon_i$. For $p=1$ from (1), (2) formulas are obtained to determine the largest shear stresses and angular deformations $\tau_{\max}$, $\gamma_{\max}$, when $p=2$ – intensities of stresses and strains σ_i, ε_i are obtained.

4.2. Method of determining the parameter p

In order to determine the parameter *p*, the primary data of deformation of plastic materials obtained in the principal stresses and strains at several types of plane stress state were taken. In the system of equivalent coordinates $\sigma_{eq}-\varepsilon_{eq}$ points corresponding to the experimental data, listed at different values p ($0.5<p<2.5$), were constructed. Obtained scatter plots of points in coordinates $\tau_{\max}-\gamma_{\max}$ (at $p=1$), in coordinates $\sigma_i-\varepsilon_i$ (at $p=2$) and for other values of *p* from the specified interval. The recalculation step Δp was set at level 0.001; 0.01 or 0.05.

Since the area of hardening of the deformation curve for plastic materials has a shape close to linear, as a quality functional in finding the optimal value of *p*, the maximum Pearson correlation coefficient was chosen. As another criterion for the optimality of the parameter *p* the minimum coefficient of variation as a measure of the relative scattering of points was chosen.

Pearson's correlation coefficient *R* was calculated for the whole set of points at each value of the parameter *p*. The formula was used for calculations:

$$R = \frac{1}{n-1}\frac{\sum_{i=1}^{n}((\varepsilon_{eq})_i-\bar{\varepsilon}_{eq})((\sigma_{eq})_i-\bar{\sigma}_{eq})}{\sqrt{\sum_{i=1}^{n}((\varepsilon_{eq})_i-\bar{\varepsilon}_{eq})^2}\sqrt{\sum_{i=1}^{n}((\sigma_{eq})_i-\bar{\sigma}_{eq})^2}},$$

where $\bar{\sigma}_{eq} = \frac{1}{n}\sum_{i=1}^{n}(\sigma_{eq})_i$;

n – number of observations.

As a measure of the scattering of the experimental points at each value of *p*, the average value of the index of variation was calculated *V*. The input data were divided into 5 partial intervals of equal length. The values of the coefficient of variation V_j were calculated for each *p* at partial intervals, then these values were averaged. The averaging of the values of the coefficient of variation reduced the influence of the shape and length of the primary curves on the value of the density index. Thus, to find the average value of the coefficient of variation for each value of the parameter *p*, the formula was used:

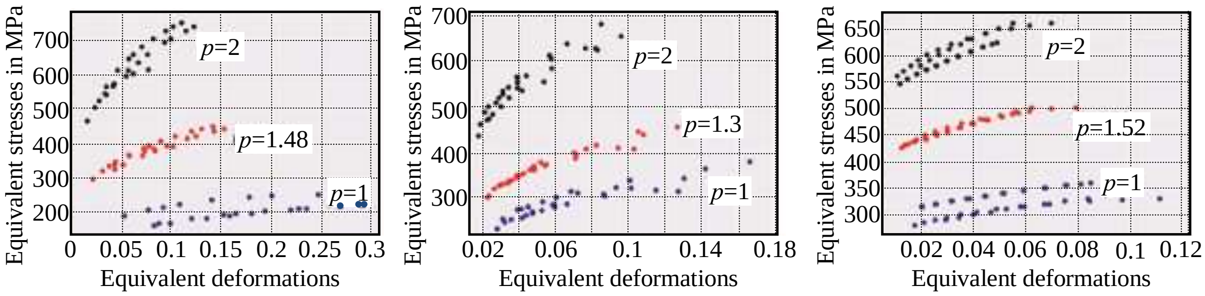
$$V = \frac{1}{5}\sum_{j=1}^{5}\frac{(STD)_j}{(\bar{\sigma}_{eq})_j},$$

where $(STD)_j$ – standard deviation of stress values $(\sigma_{eq})_i$ from *j*-th interval from the average value in this interval $(\bar{\sigma}_{eq})_j$.

4.3. Construction of a generalized curve for metal isotropic materials

Experimental data on biaxial tension of isotropic metal structural materials samples were taken from [11], [12]. The authors analyzed data for a dozen carbon and alloy steels. This publication shows the results of data processing for carbon steel 0.37 % C, high-quality carbon steel 45, and high-alloy steel 15Cr2HMoV. All data were obtained under normal conditions. Pre-treatment and condition of materials are described in primary sources.

Fig. 1 shows the scattering diagrams of experimental data calculated by formulas (1), (2) at three values *p* ($p=1$, $p=2$ and $p=p_{opt}$).

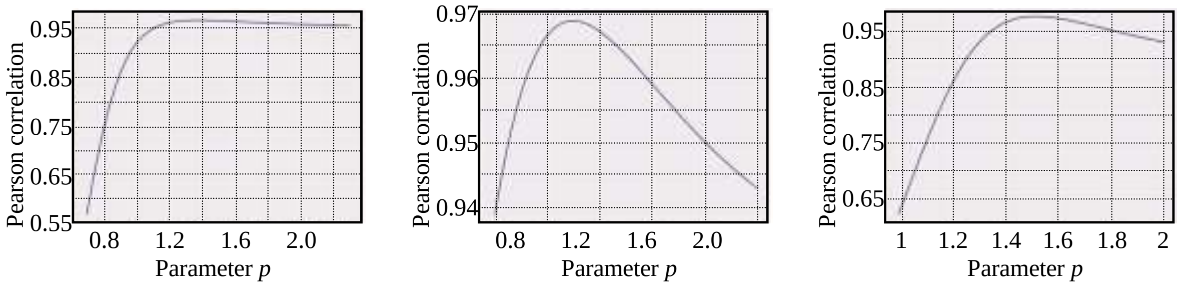


steel 0.37 % C   steel 45   steel 15Cr2HMoV

Fig. 1. Scattering diagrams of experimental points in coordinates $\sigma_{eq} - \varepsilon_{eq}$ at different p

For the considered samples of materials the smaller area covering the scattering diagrams at optimum value of parameter was visually observed. For other metallic materials similar diagrams were obtained. For the vast majority of other metallic materials and alloys, the parameter *p* took on values from the interval (1; 2). For only a few materials, the optimal parameter *p* values were outside this range.

In Fig. 2 graphs of the dependences of the Pearson correlation coefficient on the values of the parameter *p* are shown.



steel 0.37 % C   steel 45   steel 15Cr2HMoV

Fig. 2. Dependences $R(p)$ of the Pearson correlation coefficient on the parameter p

Analysis of the graphs shown in Fig. 2 showed that the dependences of the Pearson correlation coefficient on the parameter *p* reach their maximum at the selected interval. The maximum is more

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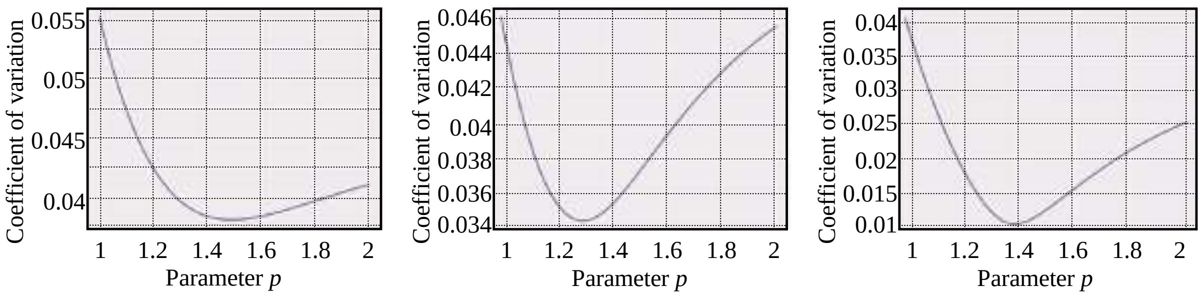
clearly observed in the case of steel 45 and is less expressed for the other two metals. A similar pattern was observed for all samples of materials considered. In some cases, the graphs for the interval $p \in [1;\ 2]$ were strictly monotonic, the maxima were observed at the ends of the segment or outside it, with a slight deviation.

In Fig. 3 graphs of dependences of the coefficient of variation on the parameter *p* are shown.



steel 0.37 % C | steel 45 | steel 15Cr2HMoV

Fig. 3. Dependences $V(p)$ of the coefficient of variation on the parameter p

Visual analysis of the graphs shown in Fig. 3 showed that there are minima of dependencies for $p \in [1;\ 2]$. The values of the parameter *p*, at which the coefficient of variation is minimal, are close to the values obtained under the condition of the Pearson correlation coefficient maximum.

Approximate values of the parameter p and the corresponding quality indicators of the model are given in Table 1. Here $R_{\max}$ – the maximum value of the Pearson correlation coefficient for $p \in [1;\ 2]$, $p(R_{\max})$ – the value of the parameter *p* at which the maximum of the Pearson correlation coefficient was reached. The minimum value of the average coefficient of variation *V* is denoted as $V_{\min}$, the value of the parameter *p*, at which $V_{\min}$ was achieved, is denoted as $p(V_{\min})$.

Table 1

Approximate values of the parameter p and quality indicators of the model (1), (2)

Steel grade	$R_{\max}$	$p(R_{\max})$	$V_{\min}$	$p(V_{\min})$
steel 0.37 % C	0.970	1.48	3.81 %	1.50
steel 45	0.968	1.30	3.44 %	1.32
steel 15Cr2HMoV	0.975	1.52	1.03 %	1.39

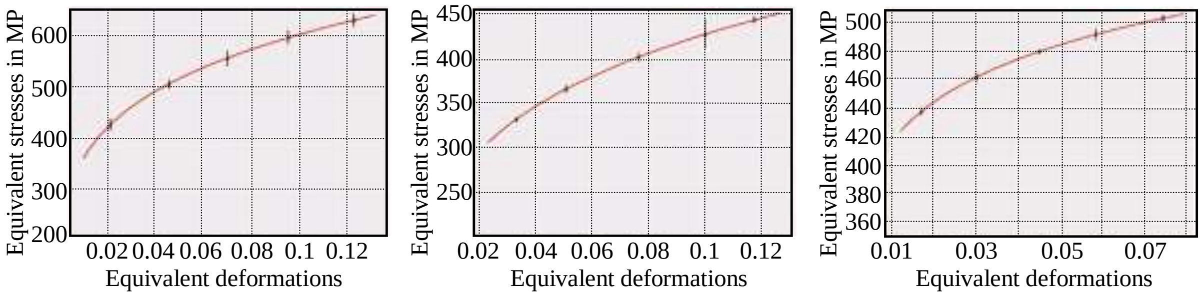
High values of the Pearson coefficient correlate with low values of the coefficient of variation, which indicates the adequacy of the chosen approach to estimating the relative density of the location of points obtained at different values of the parameter *p*. There are some deviations in the optimal values of *p* obtained by the quality functional and error functions. This can be explained by the accumulated errors, including at the stage of measurement, construction of primary deformation curves, digitization of data borrowed from external sources, and rounding of the calculated data.

4.4. Approximation of deformation curves

A power model was used to approximate the deformation curve in equivalent coordinates:

$$\sigma_{eq}{}^{*} = A \cdot (\varepsilon_{eq})^{B}, \qquad (3)$$

where *A*, *B* – model parameters: modulus and strengthening index, respectively. In Fig. 4 the approximation deformation curves constructed on the areas of strengthening at $p(R_{\max})$ and standard deviation of experimental points from the calculated curve are shown.



steel 0.37 % C   steel 45   steel 15Cr2HMoV

Fig. 4. Approximation strengthening curves at optimal values p

The calculated parameters of the model (3) and quality indicators – the index of determination R^2, the average value of errors *MR* and the average relative absolute deviation of the experimental points from the approximation curve *AAE* are shown in Table 2.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}((\sigma_{eq})_i - (\sigma_{eq}{}^*)_i)^2}{\sum_{i=1}^{n}((\sigma_{eq})_i - \bar{\sigma}_{eq})^2}; \quad (4)$$

$$MR = \frac{1}{n}\sum_{i=1}^{n}((\sigma_{eq})_i - (\sigma_{eq}{}^*)_i); \quad (5)$$

$$AAE = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|(\sigma_{eq})_i - (\sigma_{eq}{}^*)_i\right|}{(\sigma_{eq})_i}\cdot 100\%. \quad (6)$$

In the formulas (4) – (6) $(\sigma_{eq}{}^*)_i$ – values of equivalent stresses obtained by formula (3).

Table 2

Calculated parameters of model (3) and approximation quality indicators

Steel grade	*A*	*B*	R^2	*MR*	*AAE*
steel 0.37 % C	1001.88	0.222	0.971	0.210	2.2 %
steel 45	721.41	0.229	0.973	0.047	1.24 %
steel 15Cr2HMoV	643.27	0.095	0.980	0.011	0.56 %

All indicators of the quality of the approximation were checked using Fisher’s statistics and are statistically significant.

The selection of criteria for estimating the relative density of points and the type of model for approximating the deformation curve remain controversial. The fit curves constructed by the authors on the basis of a logarithmic model $\sigma_{eq}{}^* = A + B\ln\varepsilon_{eq}$, gave commensurate indicators of quality.

5. Conclusions

The article proposes a universal method for constructing a generalized strengthening curve for plastic materials, which is consistent with the classical approaches of von Mises and Tresca, but takes into account the deviation of experimental data for the class of plastic isotropic metallic materials. The method of constructing a generalized deformation curve invariant with respect to the type of stress state is described.

The calculation of the parameter p of the proposed model (1) – (2), the parameters of the approximation dependences and quality indicators was performed using a computer program using a programming language Python.

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Analysis of the calculations performed for a series of metallic plastic materials showed that it is possible to determine such a calculated value *p* of the constant material for which the scattering field of the experimental data in the coordinates $\sigma_{eq} - \varepsilon_{eq}$ is the smallest in area. This confirms the hypothesis of the existence of a single deformation curve. At optimal parameter *p* values, it is possible to obtain a regression equation for a single deformation curve with the best quality indicators.

To obtain the value of the parameter *p* as a constant material, you need to have the results of a few simple experiments. For the most accurate calculation of the material constant *p* it is necessary to minimize the impact of errors at the stages of preparation, testing and processing of results. Testing the model for a larger number of metallic plastic materials and selection of additional quality metrics will allow to describe with satisfactory accuracy the generalized deformation curve analytically and to predict the stress-strain state of the material in the strengthening interval.

In combination with the methods of taking into account the geometry of structures, the obtained generalized curve can be used to predict the values of real stresses occurring in structural elements under load and to improve approaches to estimating the realistic factor of safety.

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Козбур Галина Володимирівна; Kozbur Halyna, ORCID: https://orcid.org/0000-0003-3297-0776
Шкодзінський Олег Ксаверович; Shkodzinsky Oleh, ORCID: https://orcid.org/0000-0002-9983-0471
Гладьо Ольга Юріївна; Hlado Olha, ORCID: https://orcid.org/0000-0003-1798-4934

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