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APPLICATION OF HYSTERESIS ENVELOPE MODEL TO STEEL BEAM-TO-COLUMN BOLTED JOINT

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Abstract. The paper demonstrates the applications of the hysteresis envelope model on the example of a double extended end plate beam-to-column bolted joint. The hysteresis envelope model represents a new analytical trilinear model that can describe the cyclic behaviour of joints in a moment-resisting steel frame and is suitable for nonlinear static pushover analysis. The principle of determining the parameters of the hysteresis model is based on the monotonic curve of joint, which can be determined by applying the Component method using commercial software for the joint design. After trilinear idealisation of nonlinear $M - \phi$ curve, the parameters of the hysteresis envelope model are then obtained by multiplying the parameters of the monotonic model with a nonlinear exponential function. Predicting the cyclic behaviour of the joint using the hysteresis envelope model is satisfactory for further practical application.

Keywords: hysteresis envelope model, beam-to-column bolted joint, component method, monotonic $M - \phi$ curve, IDEA StatiCa.

1. Introduction. The effect of the real behaviour of steel joints on the seismic response of steel moment-resisting frames has long been recognised as a crucial aspect to ensuring a safe structural response. Common practise is to increase the hysteretic energy as much as possible through inelastic behaviour, using the ductile properties of structures [1]. In order to achieve the best seismic performance, in the case of moment-resisting frames, the steel structure must be designed to allow the development of plastic deformations in specific parts of the structure, such as the ends of beams or in the beam-to-column joints, but never in the columns, with the exception of the base of first-storey columns [2]. Therefore, the ductility of steel frames is deeply influenced by the behaviour of their joints. To include their effects in frame design, the $M - \phi$ curve of the joint must be represented in the appropriate analytical form. For seismic design, the $M - \phi$ curve is cyclical and must include degradation effect of strength and stiffens which arise as the number of cycles increases. Two different approaches can be taken in the design of beam-to-column joints of moment resisting frames. The first approach is based on the location of the dissipative zone at the beam ends, which means that the joint must have sufficient strength to ensure this. The second approach relies on energy dissipation through the plastic bending of the joint. This means that energy is dissipated through the joint components.

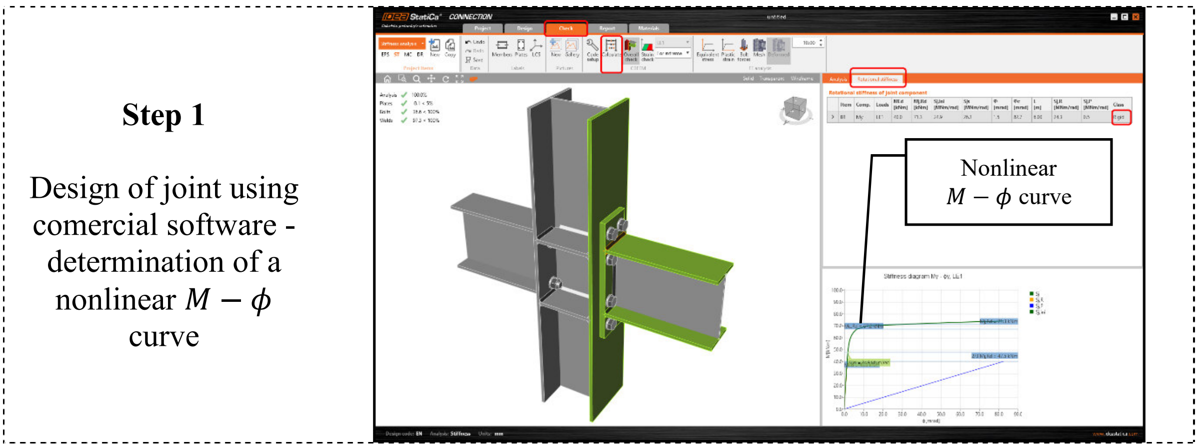
Eurocode 8, Part 1 [3] provides rules for the design and detailing of joints subjected to seismic loading. In particular, for moment-resisting frames, it is specifically allowed to use dissipative semi-rigid and/or partial strength joints. The effect of joint deformation on the global response of a structure can be determined using nonlinear static pushover analysis. Numerous studies [4–7] have analysed the influence of monotonic behaviour of joints on seismic response of moment-resisting steel frames. However, monotonic models have limitations because they do not provide sufficient information about the hysteresis behaviour of the joints. Nonlinear static analysis of structures is mainly carried out in a way that takes the monotonic properties of the joints, which is considered quite conservative.

Lignos and Krawinkler (2011) [8] proposed the modified Ibarra-Krawinkler (IK) deterioration model that establishes strength bounds on the basis of a monotonic backbone curve and a set of rules that define the characteristics of hysteretic behaviour. The backbone curve is defined by three strength parameters and four deformation parameters. The modified IK model is applied to the beam-to-column joint in which inelastic deformations are primarily concentrated in the flexural plastic hinge regions of the beam sections. The modified IK model is also applied to the specimens that have reduced beam sections in which plastic hinges develop away from the beam-to-column joint.

In this paper, the hysteresis envelope model is presented, which was developed by Krolo and Grandić (2021) [9]. The hysteresis envelope model represents a simple way of modelling the joints of moment-resisting steel frames for nonlinear static pushover analysis. The aim of this paper is to demonstrate the application of the new hysteresis envelope model to the example of a double-extended beam-to-column bolted joint. The proposed hysteresis envelope model of joint is applicable to moment-resisting frames that are designed in such a way that during earthquakes, all plastic deformations primarily occur in the joint instead of columns and beams. As recommended by Eurocode 3, Part 1-8 [10], the joint resistance is equal to or less than the resistance of the connected beam. The ratio of the resistance of the column in relation to the resistance of the beam must be at least 30% higher to satisfy the criterion "strong column–weak beam". The proposed hysteresis envelope model could be further applied in the nonlinear static pushover analysis of moment-resisting steel frames, and enables a better prediction of the structures behaviour under seismic action.

2. Steel joints under cyclic loading. Predicting the behaviour of steel joint under cyclic loading can be quite complex and impractical in engineering practice. Numerical approaches based on finite element methods require lengthy calculations and are very exhausting and time-consuming in practice. Laboratory tests, on the other hand, can be time-consuming and costly. A hysteresis envelope model is presented in this paper as a simple way of modelling the joints of moment-resisting steel frames for nonlinear static pushover analysis. The proposed hysteresis envelope model establishes bounds on the basis of a monotonic backbone curve by defining a correction factor to correct the monotonic trilinear moment-rotation response of the joint.

The procedure of determining the parameters of the hysteresis envelope model is shown in Figure 1 through three steps. In the first step it is necessary to define monotonic curve $M - \phi$ of joints. Monotonic behaviour of joints can be achieved by applying the principles of the Component method, which is accepted in Eurocode 3 for the design of joints in steel structures and is available in numerous commercial software (Step 1). The nonlinear moment-rotation ($M - \phi$) curve, obtained by the Component method, should be idealised with a trilinear curve (Step 2). The parameters of the hysteresis model are then obtained according to Eq. 1 (Step 3).



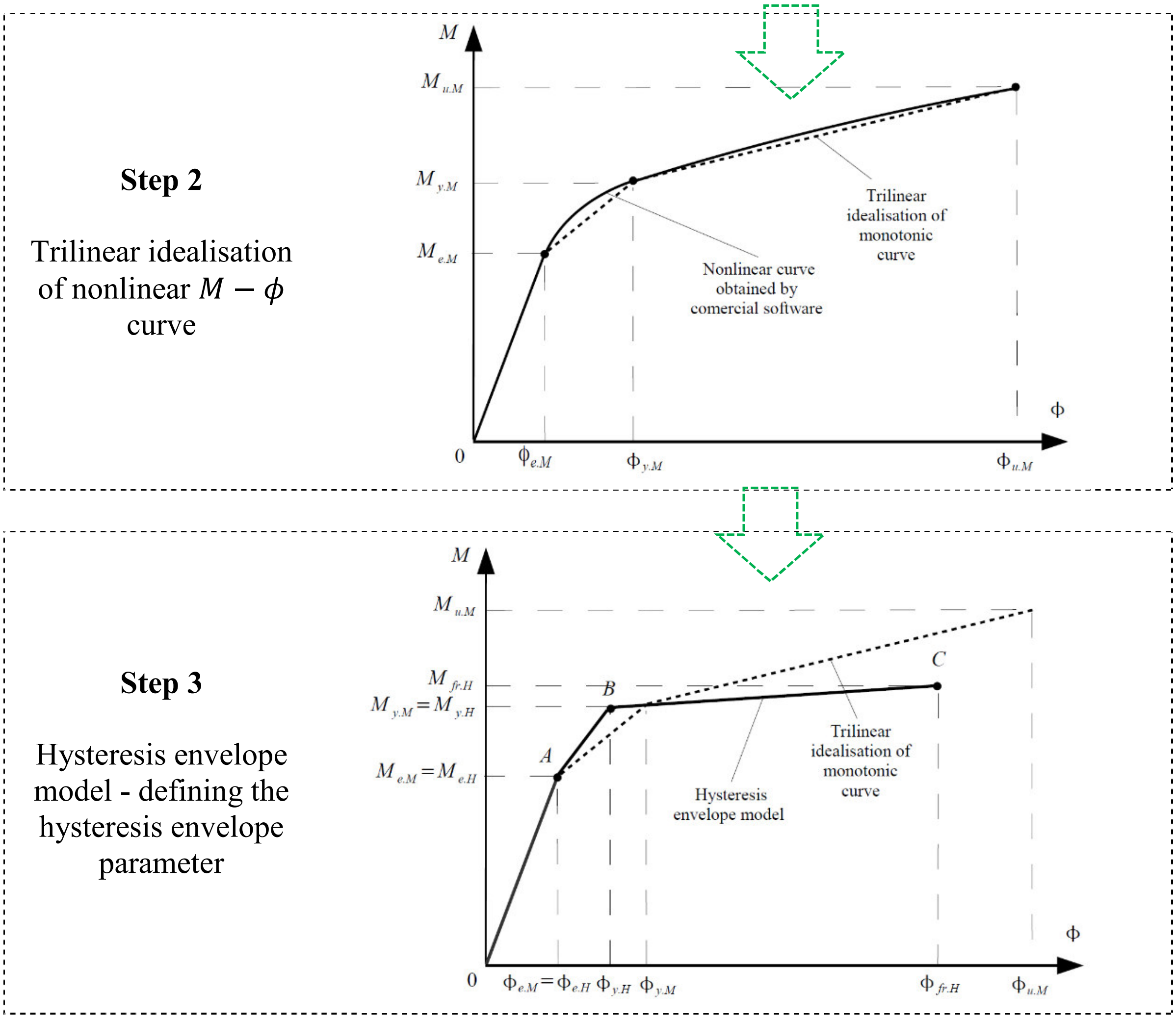


Figure 1. Procedure for determining hysteresis envelope model parameters

2.1 Hysteresis envelope model. The hysteresis envelope model forms the basis for modelling the joint for nonlinear static pushover analysis (Figure 1, Step 3). The hysteresis envelope model is defined by three strength parameters ($\boldsymbol{M_{e.H}}$ = bending moment in the elastic region, $\boldsymbol{M_{y.H}}$ = bending moment at full plasticization, and $\boldsymbol{M_{fr.H}}$= bending moment at fracture), and three deformation parameters ($\boldsymbol{\phi_{e.H}}$ = rotation of the joint in the elastic region, $\boldsymbol{\phi_{y.H}}$= rotation of the joint at full plasticization, and $\boldsymbol{\phi_{fr.H}}$= rotation of the joint at fracture).

The elastic part (0-A) does not change under monotonic and cyclic loading, which means that the bending moment and rotation in the elastic region can be adopted from the monotonic behaviour of the joint ($M_{e.H} = M_{e.M}$, $\phi_{e.C} = \phi_{e.M}$). The line (A-B) represents the full plasticization of the joint with bending moment ($M_{y.H} = M_{y.M}$), and rotation of the joint $\phi_{y.H}$. The line (B-C) represents the hardening area and degradation of strength after which fracture occurs in the joint. The position of point C has a rotation value corresponding to the fracture of the joint $\phi_{fr.H}$, and the bending moment $M_{fr.H}$.

The dependency between monotonic parameters and hysteresis envelope model parameters is defined by multiple nonlinear exponential regression as a function of the independent variables t, and p, where p is the thickness of the end-plate, and t is the vertical spacing between the bolt rows, as in (1). The following terms define the hysteresis envelope model:

$$(0-\text{A}) \begin{cases} M_{e.H} = M_{e.M} \\ \phi_{e.H} = \phi_{e.M} \end{cases} \quad \phi \leq \phi_{e.\text{H}}$$

$$(\mathrm{A}-\mathrm{B})\begin{cases} M_{y.H} = M_{y.M} \\ \phi_{y.\mathrm{H}} = \phi_{y.\mathrm{M}}(0.2341t^{-0.208}p^{0.3293}) \end{cases} \phi_{e.H} < \phi < \phi_{y.\mathrm{H}} \quad (1)$$

$$(B-C)\begin{cases} M_{fr.H} = M_{u.\mathrm{M}}(0.5024t^{0.4429}p^{-0.131}) \\ \phi_{fr.H} = \phi_{u.M}(0.0059t^{0.3086}p^{0.8002}) \end{cases} \phi_{y.\mathrm{H}} < \phi < \phi_{fr.\mathrm{H}}$$

2.2 **Application of hysteresis envelope model.** The hysteresis envelope model was applied to the case of double extended end-plate bolted beam-to-column joints. The joints consist of a steel beam made of IPE400 profile that is welded to the end-plate, which is then bolted to a column flange made of HEA 360 profile with 8 high-quality M20 preload bolts of steel grade 10.9 (see Figure 2). The friction coefficient of the contact surface was considered to be 0.44. The specimen was fabricated from S355 steel. The yield strength and ultimate strength value of steel plates are 384MPa and 552MPa, respectively, while the Young's modulus is equal to 199000MPa. Material parameters of high-strength bolts are selected by Wang et al. [11], and are given in Table 1.

Table 1 – Material properties of high-strength bolt class 10.9

Stress [MPa]	990	1160
Strain [–]	0.0048	0.136

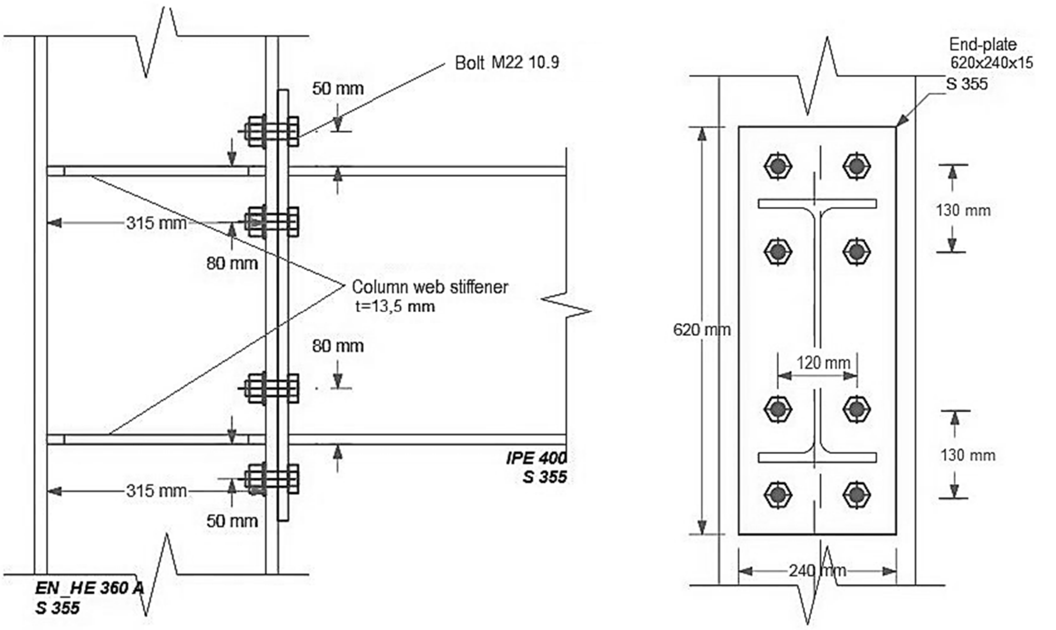


Figure 2. Dimension of beam-to-column joint [mm]

Determination of hysteresis envelope model parameters was performed through three steps according to the procedure shown in Figure 1.

Step 1. To determine the monotonic nonlinear response of the beam-to-column joint, an IDEA StatiCa software was used [12]. The model of the double extended beam-to-column bolted is shown in Figure 3. Software uses an elastic-plastic material model of steel with a nominal yielding plateau slope of tan-1(E/1000), where E is the modulus of elasticity of steel (see Figure 4). By performing stiffness analysis, the nonlinear $M-\phi$ curve is obtained.

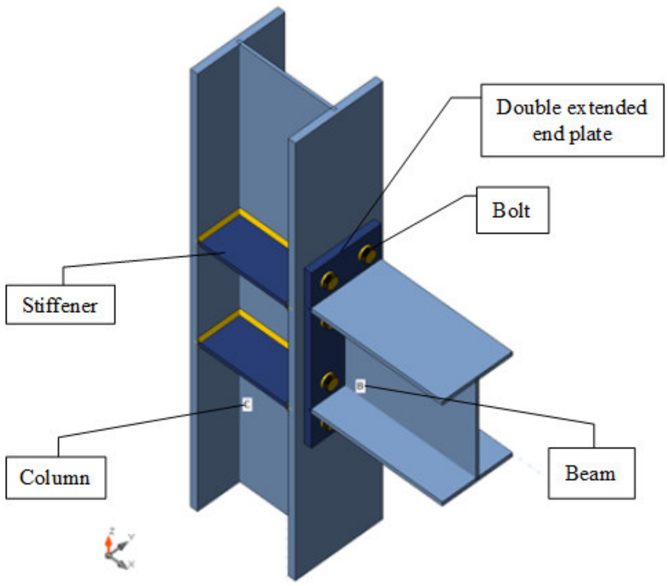


Figure 3. Model of beam-to-column joint in IDEA StatiCa software

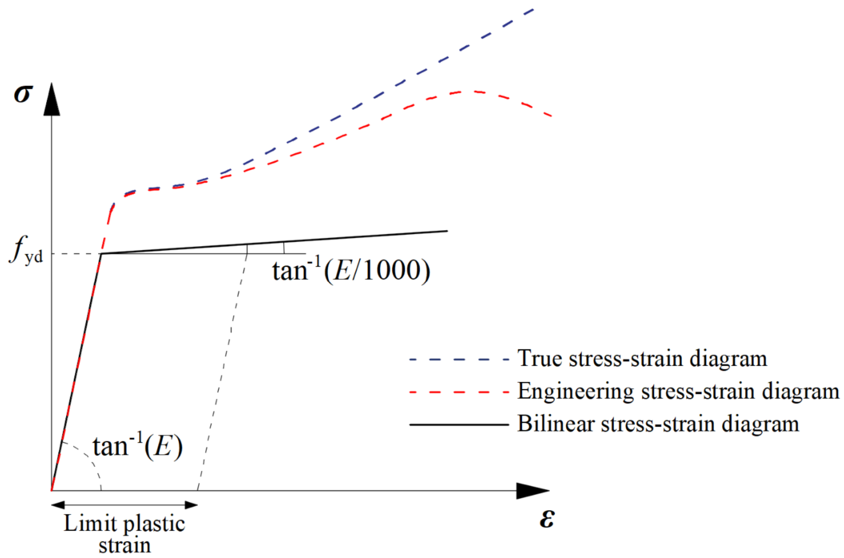


Figure 4. Elasto-plastic material model of steel in IDEA StatiCa [12]

Step 2. The nonlinear moment-rotation ($M - \phi$) curve, obtained by the stiffness analysis, was idealized with a trilinear curve in a way that defines moments and rotations at the end of each linear segment of the curve. The first linear segment represents the elastic region of the $M - \phi$ curve and it is determined by moment $M_{e.M}$ and rotation $\phi_{e.M}$. The second linear segment of the trilinear curve represent the part between elastic behaviour and full plasticization of joint and it is determined by moment $M_{y.M}$ and rotation $\phi_{y.\mathrm{M}}$. The last segment of the trilinear curve represents the part between full plasticization and ultimate strength of the joints which corresponds to the strength of the joint, when the steel material has reached its tensile strength. It is determined by moment $M_{u.M}$ and rotation $\phi_{u.\mathrm{M}}$. Trilinear curve parameters are given in Table 2. The parameters obtained by the *IDEA StatiCa* were compared with the parameters obtained by numerical simulation in ABAQUS. To make the parameters comparable, the calculations in *IDEA SatiCa* were made with a partial safety factor $\gamma_{M2} = 1$ instead of $\gamma_{M2} = 1.25$. Details on the FEM model of beam-to-column joint are available in [9]. The differences between the parameters obtained by commercial software and numerical simulation are obvious, and the largest difference was obtained for $M_{u.M}$ and is equal to 15.76%.

Table 2 – Parameters of trilinear model

Parameters	IDEA StatiCa	FEM	Δ [%]
$M_{e.M}$ [kNm]	234	227.7	2.77
$\phi_{e.M}$ [-]	0.0077	0.009	14.45
$M_{y.M}$[kNm]	351.2	333.01	5.46
$\phi_{y.M}$ [-]	0.0263	0.023	14.35
$M_{u.M}$ [kNm]	361	428.55	15.76
$\phi_{u.M}$ [-]	0.085	0.083	2.4

Step 3. The parameters of the trilinear model from Table 2 were applied for the calculation of the parameters of the hysteresis envelope model, as in Eq. (1). The obtained values are given in Table 3. For comparison, in Table 3 are given parameters for hysteresis envelope model obtained by numerical simulation in ABAQUS using finite element method (FEM). As expected, differences between the parameters obtained by commercial software and FEM are significant. The largest difference was obtained for $M_{u.H}$ and is equal to 14.24%.

Table 3 – Parameters of hysteresis envelope model

Parameters	IDEA StatiCa	FEM	Δ [%]
$M_{e.H}$ [kNm]	234	227.7	2.77
$\phi_{e.H}$ [-]	0.0077	0.009	14.45
$M_{y.H}$[kNm]	351.2	333.01	5.46
$\phi_{y.H}$ [-]	0.017	0.016	6.25
$M_{fr.H}$ [kNm]	318.07	370.9	14.24
$\phi_{fr.H}$ [-]	0.057	0.055	3.63

The reason for the differences lies in the fact that IDEA StatiCa software uses an idealised bilinear elastic-plastic material model. On the example of a beam-to-column joint, the influence of the limit value of plastic strain on the moment resistance was studied and reported in [12]. By varying the limit plastic strain from 2% to 8%, the change in moment resistance was less than 4%.

3. Conclusions. In this paper, the procedure of applying a new hysteresis envelope model to the double extended beam-to-column bolted joint, using commercial software is presented. Based on the conducted studies, the following conclusions can be drawn:

- The hysteresis envelope model represents the simple trilinear model which describes the cyclical behaviour of the beam-to-column joint
- The application of commercial software allows easy and fast determination of the monotonic behaviour of the joint, which is used as a basis for determining the parameters of the hysteresis envelope model.
- The behaviour of the joint after the onset of plasticization cannot be precisely defined using commercial software since the program uses a simplified elastoplastic material model.

In future research, the plan is to implement a hysteresis envelope model to describe the behaviour of joints in moment-resisting frames and to investigate their influence on seismic response obtained by nonlinear static pushover analysis.

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ЗАСТОСУВАННЯ МОДЕЛІ ГІСТЕРЕЗИСНОЇ ОГИНАЮЧОЇ ДЛЯ БОЛТОВОГО З'ЄДНАННЯ СТАЛЕВОЇ БАЛКИ З КОЛОНОЮ

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Анотація. У роботі представлено практичне застосування моделі гістерезисної огинаючої на прикладі болтових з'єднань балки та колони. Модель гістерезисної огинаючої є новою аналітичною трилінійною моделлю, яка може описати циклічну поведінку з'єднань у стійкій до моменту сталевій рамі та підходить для нелінійного аналізу статичної тяги. Принцип визначення параметрів моделі гістерезису заснований на нелінійній кривій з'єднань, яку можна визначити компонентним методом за допомогою програмного забезпечення для проектування з'єднань. Криву нелінійного крутіння моменту, отриману програмним забезпеченням, слід ідеалізувати за допомогою трилінійної кривої. Потім параметри моделі гістерезисної огинаючої отримують шляхом множення параметрів нелінійної моделі на нелінійну експоненціальну функцію. Прогнозування циклічної поведінки з’єднання за допомогою моделі гістерезисної огинаючої є задовільним для подальшого практичного застосування.

Ключові слова: модель гістерезисної огинаючої, болтове з'єднання балка-колон, компонентний метод, нелінійна крива M – ϕ, IDEA StatiCa.

ПРИМЕНЕНИЕ МОДЕЛИ ГИСТЕРЕЗИСНОЙ ОГИБАЮЩЕЙ ДЛЯ БОЛТОВОГО СОЕДИНЕНИЯ СТАЛЬНОЙ БАЛКИ С КОЛОНОЙ

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Аннтотация. В работе представлено практическое применение модели гистерезисной огибающей на примере болтовых соединений балки и колонны. Модель гистерезисной огибающей является новой аналитической трехлинейной моделью, которая может описать циклическое поведение соединений в устойчивой к моменту стальной раме и подходит для нелинейного анализа статической тяги. Принцип определения параметров модели гистерезиса основан на нелинейной кривой соединений, которую можно определить компонентным методом с помощью программного обеспечения для проектирования соединений. Кривую нелинейного кручения момента, полученную с помощью программного обеспечения, следует идеализировать с помощью трехлинейной кривой. Затем параметры модели гистерезисной огибающей получают путем умножения параметров нелинейной модели на экспоненциальную нелинейную функцию. Прогнозирование циклического поведения соединения с помощью модели гистерезисной огибающей удовлетворительно для дальнейшего практического применения.

Ключевые слова: модель гистерезисной огибающей, болтовое соединение балка-колонна, компонентный метод, нелинейная кривая M – ϕ, IDEA StatiCa.