CZASOPISMO INŻYNIERII LĄDOWEJ, ŚRODOWISKA I ARCHITEKTURY
JOURNAL OF CIVIL ENGINEERING, ENVIRONMENT AND ARCHITECTURE
JCEEA, t. XXXII, z. 62 (4/15), październik-grudzień 2015, s. 357-367

Krzysztof OSTROWSKI[1]
Aleksander KOZŁOWSKI[2]

HIERARCHICAL VALIDATION OF FEM MODELS OF BOLTED JOINTS

The results of multistage hierarchical validation of the advanced FEM models used to define rotation capacity of steel joints have been presented in the paper. Validation process has been carried out for different models with various level of complexity. Comparative analysis of the FEM models has been conducted in relation to results of own laboratory tests. Developed methodology of formation material characteristic was a base for further analysis of advanced models of end plate beam-to- column connections of in the area of forecasting rotation capacity of the joint and the whole M-ϕ curve.

Keywords: validation of FEM models, material characteristic, Ramberg-Osgood's function

1. Introduction

Finite Element Method (FEM) is a very useful tool for the static-strength analysis of complex structural systems. One of the main condition to obtain actual and reliable results of FEM is to apply proper strain-stress material characteristics.

The first trial which described analytically strain-stress relationship of steel material was proposed by Walter Ramberg and William Osgood in 1941. Their assumption was based on the previous work of Nadai from 1939. After some modifications done by Rasmussen [1], full range of σ–ε curve is available. Nonlinear material behavior described by Ramberg – Osgood function found application in stainless steel codes, like EN 1993-1-4, USA code ASCE, Australians code AS/NZS 4673 and South Africa code SABS. Nowadays research is conducted to implement it also to carbon steel codes.

[1] Author for correspondence: Krzysztof Ostrowski, MTA Engineering Sp. z o. o., ul. Poniatowskiego 14, 35-026 Rzeszow, +48 609 774 850, krzysztof.ostrowski@mta-online.net
[2] Aleksander Kozłowski, Rzeszow University of Technology, ul. Poznanska 2, 35-959 Rzeszow, kozlowsk@prz.edu.pl

Following rapid development of computers power, which took place in last twenty years, FEM becomes nowadays very popular and available tool allowing recognizing complex processes in investigated objects. Results of FEM can be considered as satisfactory if they are complying with results from experimental tests. To obtain this, it is necessary to calibrate FEM models. Best way to calibrate FEM models is to conduct hierarchical validation, by comparison their results to laboratory tests results. The main criterion used in validation process is the ratio of fitting σ–ε curve obtained from experiment with this one obtained from FEM analysis.

As an example of validation of FEM model can be mentioned research done by Girao [2], in which 32 T-stubs were experimentally investigated. Bolts of grade 8.8 and 10.9, and steel grades S355 and S690 were used. Obtained material characteristics were applied in comparison to FEM results and were used in further research [3]. Also Beg, Zupancic and Vayas [4] conducted advanced research using FEM which aimed in assessment of rotation capacity of beam-to-column end - plate bolted joints. Firstly they experimentally tested tensile T-stubs made of HEA 260 and HEB 200 profiles, and then, after calibration of FEM model, used it to investigate joint loaded by bending moment.

2. Theoretical basis of material characteristics

According to Appendix C of code [5], the following material models can be used:

a) elastic-plastic without strain hardening,
b) elastic-plastic with a pseudo strain hardening,
c) elastic-plastic with linear strain hardening,
d) true stress-strain curve calculated from a technical stress-strain curve.

Material characteristics which can be applied in FEM analysis are depicted in Fig. 1. The first three models represent conservative attempt and are used rather in material engineering research. Material characteristics which do not possess logarithmic strain lead to results there allowable stress and/or strain are reached earlier in the analysis. Only one characteristic which fulfills actual deformation of investigated system is stress-strain curve shown in Fig. 1d. Curve 2 is so called engineering curve referred to initial cross section of tension member A_0, while curve 1 is related to real, actual cross section A, what presents actual stress.

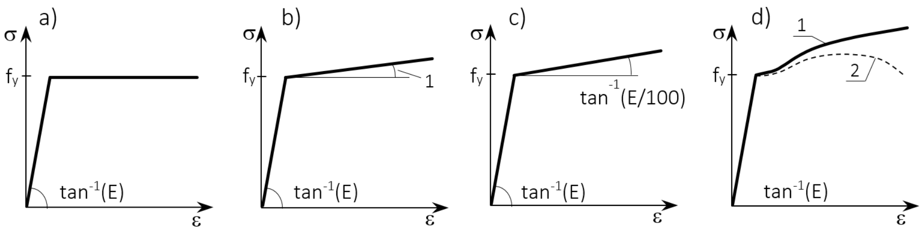

Fig. 1. Models of steel characteristics included in PN-EN 1993-1-5

Rys. 1. Modele charakterystyki stali zawarte w PN-EN 1993-1-5

Stress-strain relationship for small strains is described by standard Ramberg – Osgood function:

$$\varepsilon = \frac{\sigma}{E_0} + 0,002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \text{ for } \sigma \le \sigma_{0.2}. \tag{1}$$

Value of strain $\varepsilon_{0.2}$=0,2% is achieved for stresses by which non-linear behavior starts (Fig. 2a). Rasmussen [1] made modification of equation (1) to the form presented by eq. (2):

$$\bar{\varepsilon} = \frac{\bar{\sigma}}{E_0} + \bar{\varepsilon}_{u_p}\left(\frac{\bar{\sigma}}{\bar{\sigma}_u}\right)^m \text{ for } \sigma \ge \sigma_{0.2}, \tag{2}$$

where: $\bar{\varepsilon}$ and $\bar{\sigma}$ are modified values of strain and stress given by:

$$\bar{\varepsilon} = \varepsilon - \varepsilon_{0.2}, \tag{3}$$

$$\bar{\sigma} = \sigma - \sigma_{0.2}. \tag{4}$$

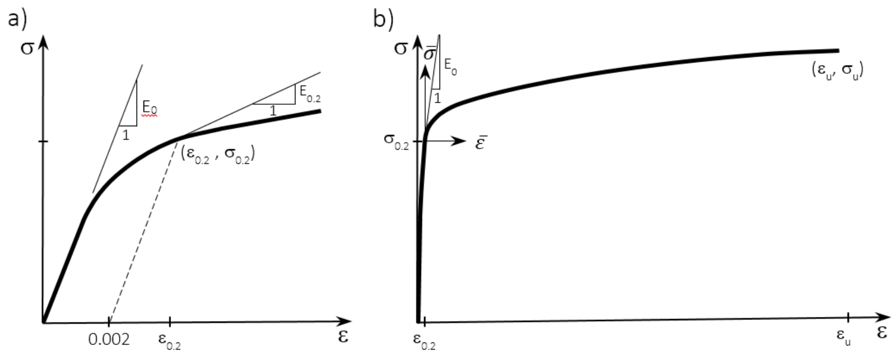

Fig. 2. Strain-stress curve: a) initial stage, b) full characteristics [5]

Rys. 2. Krzywa naprężenie-odkształcenie: a) stan początkowy, b) pełna charakterystyka [5]

Exponent "m" is described by following relation:

$$m = 1 + 3{,}5\frac{\sigma_{0.2}}{\sigma_u}\,. \tag{5}$$

After substituting eq. (3) and (4) to (2) full range of strain-stress relationship is reached in the form:

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^n & \text{for } \sigma < \sigma_{0.2} \\ \dfrac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\dfrac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} & \text{for } \sigma > \sigma_{0.2} \end{cases}\,. \tag{6}$$

Equation (6) in slightly changed form was included in code [6] for stainless steel. Depending on required precision of calculation and expected range of strains, following three attempts in material modeling are used:

a) Strain-stress curve with strain hardening:

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E} + 0{,}002\left(\dfrac{\sigma}{f_y}\right)^n & \text{for } \sigma < f_y \\ 0{,}002 + \dfrac{f_y}{E} + \dfrac{\sigma - f_y}{E_y} + \varepsilon_u\left(\dfrac{\sigma - f_y}{f_u - f_y}\right)^m & \text{for } f_y < \sigma < f_u \end{cases}\,, \tag{7}$$

where: n –coefficient done by formula:

$$n = \frac{\ln(20)}{\ln\left(\dfrac{f_y}{R_{p0,01}}\right)}\,, \tag{8}$$

$R_{p0,01}$ – field point by 0,01 % strain,
E_y – secant modulus referred to yield point:

$$E_y = \frac{E}{1 + 0{,}002 \cdot n \cdot \dfrac{E}{f_y}}\,, \tag{9}$$

ε_u – ultimate strain referred to ultimate stress, given by:

$$\varepsilon_u = 1 - \frac{f_y}{f_u} \text{ but } \varepsilon_u \leq A, \tag{10}$$

A – strain by rapture
m – coefficient as in (5), but in the form:

$$m = 1 + 3{,}5\frac{f_y}{f_u}. \tag{11}$$

b) Strain-stress curve as in a) but based on measured data,
c) Actual strain-stress based on engineering measures:

$$\sigma_{true} = \sigma(1+\varepsilon), \tag{12}$$

$$\varepsilon_{true} = \ln(1+\varepsilon). \tag{13}$$

3. FEM model description

Finite Element Method assumes division of geometrical continuum for finite elements. Type of finite elements depends on geometry of analyzed object and adequateness application. Advanced FEM programs possess possibility to use: beam elements (one dimensional), two-dimensional elements (shells and membrane) and three dimensional elements (solids). To multi stage hierarchical validation two-dimensional (2D) and three-dimensional (3D) elements were used.

Bolts grade 10.9 (ISO 4014) and steel grades S235 and S355 were applied in FEM models. Multi-linear elastic-plastic material model was used. Contact surface between individual joint elements has been modeled as non-linear with friction coefficient μ=0.2.

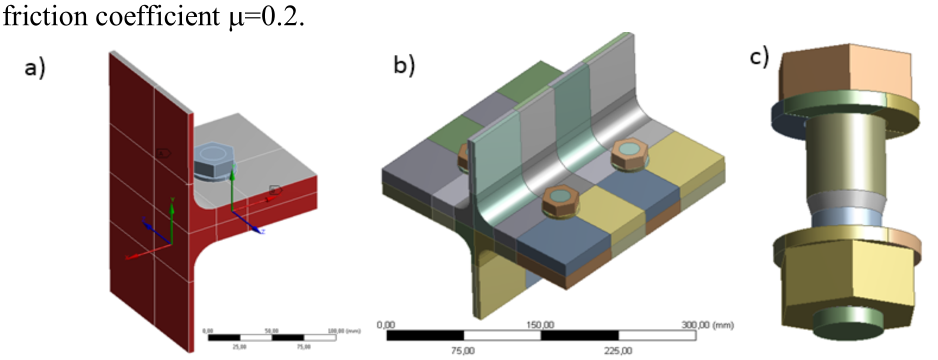

Fig. 3. FEM model used in third stage of validation: a) symmetry surfaces, b) T-stub model, c) bolt model

Rys. 3. Model MES użyty w trzecim stadium walidacji: a) powierzchnie symetrii, b) model króćca teowego, c) model śruby

Contact surfaces were introduced in the zones of contact between: end plates, washer-end plate, washer-nut, washer-head of the bolt (Fig. 4c). Additional, radial surfaces between bolt hole and bolt shank and thread were introduced in the model (Fig. 4a).

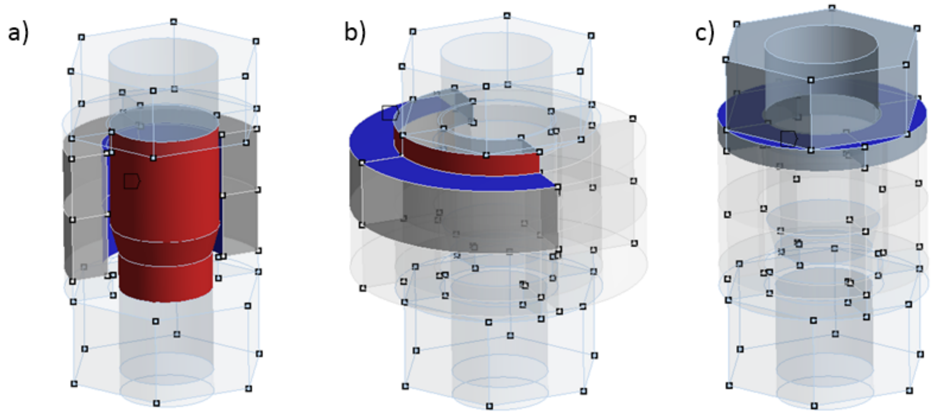

Fig. 4. Contact surface: a) radial contact bolt - end plate - column, b) anti-slip contact washer-end plate, c) contact washer-bolt head

Rys. 4. Powierzchnie styku: a) obwodowy styk śruba – blacha czołowa – słup, b) antypoślizgowy styk podkładka – blach czołowa, c) styk podkładka – łeb śruby

The last of mentioned contacts was applied to create boundary conditions to support bolt that rest on inner surface of the plate's hole caused by large joint gap. A specific type of contact surface which has been introduced into the FEM model is shown in Fig. 4b. In the initial stage of joint deformation, side surface of the washer and upper surface of the plate have no contact, but with large gap in the joint they interact between them, and plate surface is the support for the washer. Introducing such contact surface is dictated by possible occurrence of non-coinciding the FEM model caused by penetrating objects. The FEM analysis of the hierarchical validation was performed with the used of ANSYS software.

4. Stages of hierarchical validation

4.1. First stage – tensile test of steel and bolts

In FEM analysis material characteristics elaborated on the basis of experimental tensile coupon test were applied (Fig. 6). Tests were conducted in the Faculty Laboratory of Structure Investigation of WBIŚiA Rzeszow University of Technology. Measure of validation was comparison of experimental coupon test of S 235 and S355 steel and 10.9 grade bolts with the results of FEM analysis of samples models. Calibration process was performed by modification of σ–ε curve to such extend to reach acceptable level of conformity.

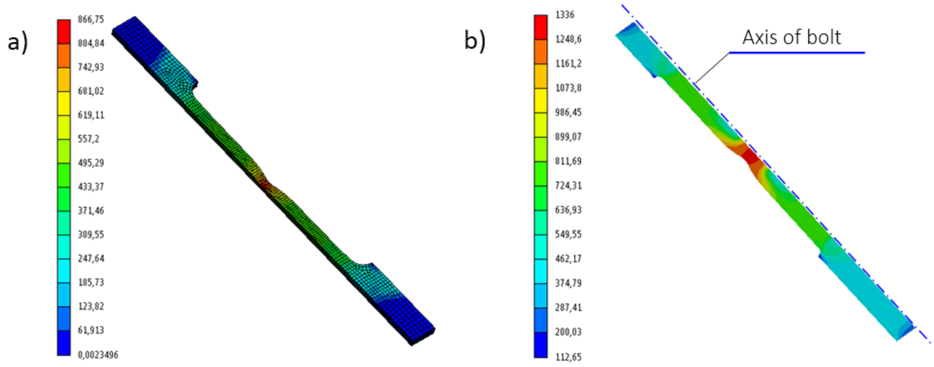

Fig. 5. FEM results: a) steel S235 (3D analysis), b) 10.9 bolt (2D analysis, radial symmetry)

Rys. 5. Rezultaty MES: a) stal S235 (analiza przestrzenna), b) śruba kl. 10.9 (analiza płaska, symetria osiowa)

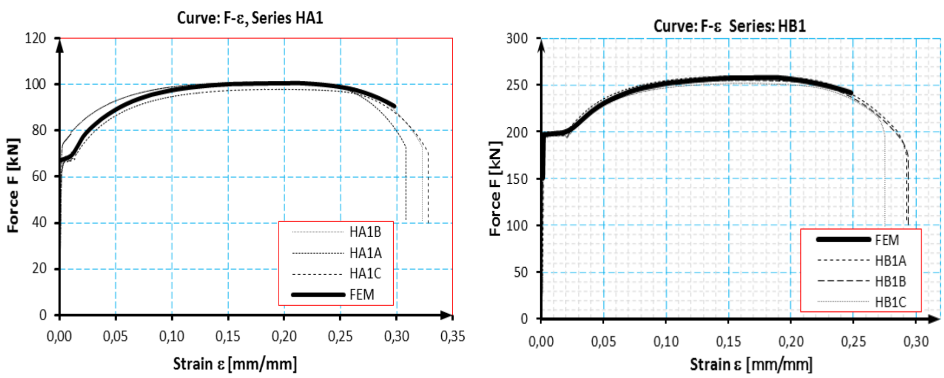

Fig. 6. Results of comparison analysis: a) steel samples S235 (3D analysis), b) steel S355 (3D analysis)

Rys. 6. Porównanie wyników analiz: a) stal próbek S235 (analiza przestrzenna), b) stal S355 (analiza przestrzenna)

In the frame of the first stage of validation 12 samples of steel material and 3 for bolts were experimentally investigated according to [7] and [8].

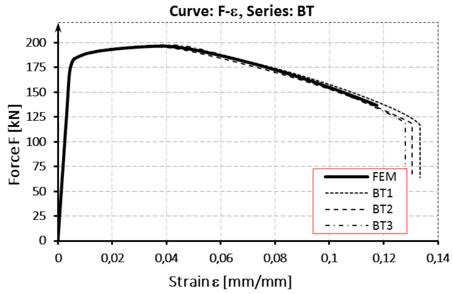

Fig. 7. Results of comparison analysis for I stage of validation of bolt 10.9 grade (2D analysis)

Rys. 7. Porównanie wyników analiz dla I stadium walidacji śrub klasy 10.9 (analiza płaska)

FEM analysis of bolts was conducted using 3D model with radial symmetry about central axis of the sample.

For steel samples 3D models with double symmetry were applied. Fig. 5 depicted maps of stress: for steel material (Fig. 5a), and for bolt (Fig. 5b). Maximum values of ultimate forces obtained in laboratory tests were: BT1 - $F_{max,1}$= 197,05 kN, BT2 - $F_{max,2}$ =195,44 kN, BT3 - $F_{max,3}$ = 197,38 kN. Value of maximum ultimate force obtained in FEM analysis was F_{FEM} = 195,49 kN. It can be concluded that obtained results are in good correlation.

4.2. Second stage of validation – tensile assembly: bolt-washer-nut

In the second stage of validation (Fig. 8) eleven samples of assembly bolt-washer-nut were experimentally investigated in tension. Results of comparison analysis are shown in Fig. 9.

Fig. 8. Tensile test of bolt-washer-nut assembly (ISO 4014)

Rys. 8. Badanie na rozciąganie zestawu łącznikowego śruba – podkładki - nakrętka (ISO 4014)

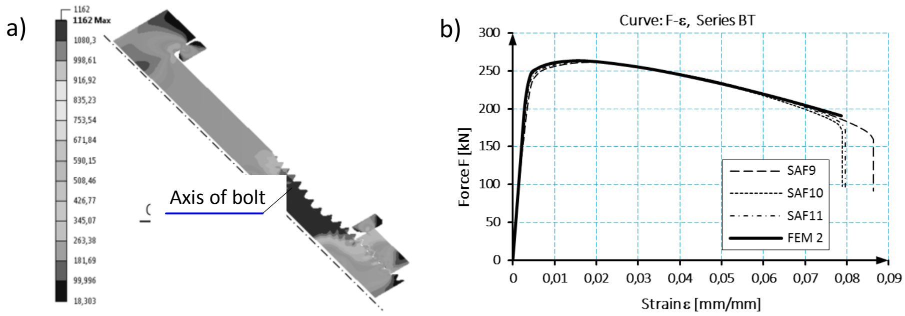

Fig. 9. Results of FEM analysis of II stage of validation; a) stress maps in the bolt, b) comparison of FEM results to test results

Rys. 9. Wyniki analizy MES II stadium walidacji; a) mapa naprężeń w śrubie, b) porównanie wyników otrzymanych z modelu MES i z badań doświadczalnych

Maximum values of ultimate forces obtained in laboratory tests were for samples: SAF9 = 261,59 kN, SAF10 = 263,18 kN, SAF11 = 262,81 kN and are very close to obtained in FEM analysis F_{FEM} = 263,66 kN.

4.3. Third stage of validation – T-stubs in tension

In the third stage of validation the following T-stubs were experimentally tested:

- series H01 – T-stub of profile HEA 240, steel: S235,
- series B01 – T-stub of profile HEB 240, steel: S355,
- series SP01 – welded T-stub: end plate 20 mm, steel S355,
- series SP02 – welded T-stub: end plate 12 mm, steel S235.

In numerical models of tested objects actual geometry projection based on exact measurement of the elements subjected to tensile test has been applied. During the measurement significant rolling deviations of the profiles have been found. Deviations dispersion in thickness of the flanges for HEB 240 (series B01) was in the range 16,35 ÷ 17,84 mm and it was the highest from all tested series. Finally, in the FEM models average value of flange thickness in relation to measurements points in area of section radius by the web were used.

Fig. 10 shows results from 3rd stage of validation. Minor discrepancy in results for tested type B01 has been found, in area of initial stage of loading the joint. The curve obtained in tested H01 type (Fig. 10a) is characterizing by relatively good matching both initial stage of loading and stage just before destruction.

a) b)

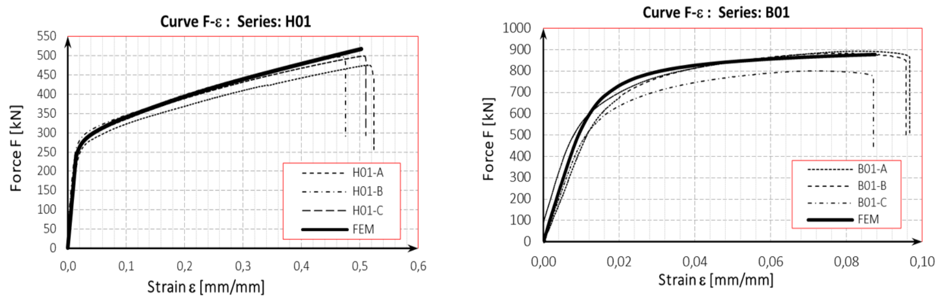

Fig. 10. Results from comparative analysis FEM III stage of validation a) Series H01 (HEA 240), b) Series B01 (HEB 240)

Rys. 10. Wyniki analizy porównawczej MES III stadium walidacji; a) serie H01 (HEA 240), b) serie B01 (HEB 240)

5. Conclusions

The main condition to get reliable results from FEM analysis of bolted beam-to-column connections is to implement material characteristics obtained as a result of multi-stage process of FEM model hierarchical validation.

The analysis of comparative charts of each stages of validation show that impact of geometrical imperfection has significant influence on projection of results from laboratory tests and ones obtained by FEM analysis. The highest discrepancies have been found in 3nd stage of validation in analysis of B01 series T-stubs (profiles HEB 240). This was caused by rolling deviations of profiles of tested end-plate connection. Different thickness of the flange on whole connecting surface causing undervalue initial stiffness $S_{j,ini}$ in comparison to stiffness obtained in FEM analysis. Material characteristic obtained in 1st stage of validation allows achieving appropriate match with response curve (F-ε) in comparison to laboratory results, but in case of use this characteristic in 3rd stage of validation there is needed to modify material characteristic in area of boundary material deformation to improve the convergence of results.

The results of the multistage hierarchical validation of FEM models carried out in this article may be used in the future for determination of joints rotation capacity in the full range of their deformability.

Bibliography

[1] Rasmussen K.J.R.: Full-range stress–strain curves for stainless steel alloys. Journal of Constructional Steel Research59 (2003) 47–61.

[2] Girao Coelho A.M., Bijlaard F., Gresnigt N., Silva L.: Experimental assessment of the behavior of bolted T-stub connections made up of welded plates. Journal of Constructional Steel Research 60 (2004) 269-311.

[3] Girao Coelho A. M., Silva L., Bijlaard F.: Finite-Element Modeling of the Nonlinear Behavior of Bolted T-Stubs Connections. Journal of Structural Engineering, 2006.132:918-928.
[4] Beg D., Zupancic E., Vayas I.: On the rotation capacity of moment connections. Journal of Constructional Steel Research 60 (2004) 601-620
[5] EN 1993-1-5 Eurocode 3: Design of steel structures, Part 1.5: Plated structural elements.
[6] EN 1993-1-4 Eurocode 3: Design of steel structures, Part 1.4: General rules, Supplementary Rules for Stainless steels.
[7] ISO 6892-1:2009 (E), Metallic materials — Tensile testing, Part 1: Method of test at room temperature.
[8] ISO 898-1 Mechanical properties of fasteners made of carbon steel and alloy steel, Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread.

WALIDACJA HIERARCHICZNA MODELU MES ZŁĄCZY ŚRUBOWYCH

S t r e s z c z e n i e

W artykule zostały przedstawione wyniki wielostopniowej walidacji hierarchicznej zaawansowanych modeli numerycznych MES przeznaczonych do określenia zdolności do obrotu węzłów stalowych. Walidacja została przeprowadzona dla różnych modeli z różnym poziomem złożoności. Prowadzone analizy porównawcze modelu MES były wykonane w odniesieniu do wyników własnych badań laboratoryjnych. Rozwinięto metodologię dotyczącą cech materiałowych i przyjęto ją jako podstawę do dalszej analizy zaawansowanych modeli blachy czołowej połączeń belek ze słupami w obszarze badań zdolności do obrotu węzła, oraz wyznaczenia całej krzywej zależności moment - obrót M-ϕ.

Słowa kluczowe: walidacja modelu MES, charakterystyka materiałowa, funkcja Ramberga-Osgooda

Przesłano do redakcji:30.05.2015
Przyjęto do druku:10.01.2016

DOI: 10.7862/rb.2015.201