Hierarchical validation of FEM models for the needs of rotation capacity determination of steel structure joints

Walidacja hierarchiczna modeli MES na potrzeby wyznaczania zdolności do obrotu węzłów konstrukcji stalowych

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The paper presents results from multistage hierarchical validation of advanced FEM models used to determine rotation capacity of steel joints. Validation process has been carried out for different models with various level of complexity. Comparative analysis of the FEM models has been carried out in relation to results obtained in laboratory tests. Developed methodology of the formation of material characteristic is a base for further analysis of advanced models of beam-to-column end-plate connections in the area of forecasting the rotation capacity curve (M-ϕ).

KEYWORDS: validation of FEM models, material characteristics, rotation capacity of joints

With the increase in the computing power of computers, the finite element method has become a widely used tool that allows recognition of complex phenomena occurring in the studied objects. The FEM results can be considered satisfactory if they are comparable with the results of laboratory tests. To get convergent results, the FEM models need to be fine-tuned. For this purpose, the method of hierarchical validation of numerical models in the comparative analysis of models of varying complexity with results of laboratory tests [1] is applied. The basic criterion in the validation process is the level of matching of the characteristics describing the behavior of the examined object subjected to FEM analysis to the characteristics obtained in laboratory tests [2, 3]. Validation includes: development of material characteristics, determination of the level of detailing the geometric details of the FEM model, selection of contact surfaces and finite element type.

The research program included validation of models using structural steels S235 and S355 as well as high strength bolts - class 10.9 (ISO4014).

Material models

The standard [4] specifies the following material models:

- elastic-plastic model without strain hardening,
- elastic-plastic model with a pseudo strain hardening,
- elastic-plastic model with linear strain hardening,
- realistic model obtained as a result of modifying the experimental stress-strain relationship (obtained on the basis of laboratory tests).

The first three models represent a conservative approach and are widely used in industrial material engineering research. Material characteristics, in which deformation is not a logarithmic function, is a kind of guarantee of reliability of the optimized objects, because in such cases, the numerical analysis always shows an earlier achievement of the state of acceptable stress and strain in comparison with the logarithmic characterization of σ-ε. The only characteristic that provides a faithful representation of the deformation of tested object is the strain-stress characteristics determined on the basis of laboratory tests and related to the instantaneous cross-sectional areas of the stretched sample, thus showing the actual strain in the deformed sample cross-section.

Stages of hierarchical validation

The hierarchical validation procedure for FEM models included the following stages:

- Stage I - stretching of steel specimens and screw samples (fig. 1a),
- Stage II - stretching bolt sets in the configuration: bolt-washer-nut (fig. 1b),
- Stage III - stretching T-stubs (fig. 1c),
- Stage IV - bending of the end-plate joint of the beam to the column in the configuration of the portal frame (fig. 1d).

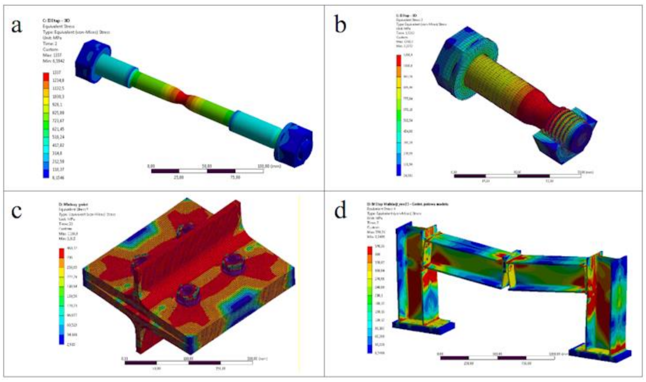

Fig. 1. FEM models used in a multistage hierarchical validation: a) I stage, b) II stage, c) III stage, d) IV stage

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The first stage of validation is determined by the force-strain characteristics (*F*-*ε*) of steel samples obtained from steel profiles (HEA 240 and HEB 240) and sheets (12 and 20 mm thick) used in the third validation stage.

Adjustment of material characteristics is achieved by modifying the stress-strain curve (*σ*-*ε*) to such a form as to obtain acceptable consistency of results with laboratory tests. The range, for which the characteristics of *σ*-*ε* is known, is determined from the formulas:

$$\sigma_{\text{true}} = \sigma(1+\varepsilon) \quad (1)$$

$$\varepsilon_{\text{true}} = \ln(1+\varepsilon) \quad (2)$$

Modification of the *σ*-*ε* curve is performed only in the range, in which behavior of the material is unknown (the *σ*-*ε* relationship cannot be determined on the basis of analytical relationships available in the literature), i.e. from the moment of narrowing in the material sample under study. The value of the maximum stress σ_u is determined on the basis of the value of the force before break of the stretched sample, referred to the value of the deformed surface area of the sample A after fracture. The maximum strain ε_u, corresponding to the maximum stress σ_u, is determined in an iterative manner, increasing the strain ε_u to such values, at which the best fit of the real characteristic *σ*-*ε* is obtained.

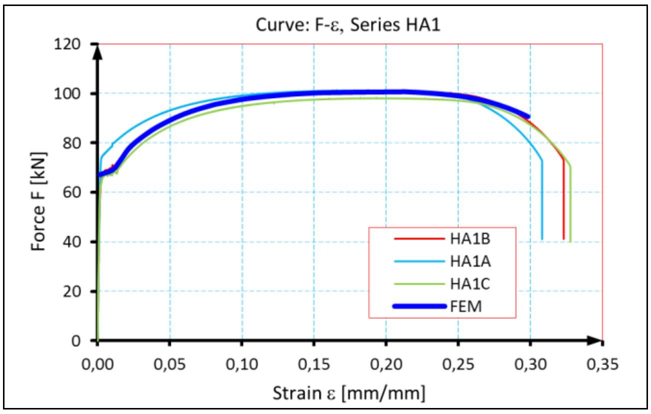

Fig. 2. Results of the FEM comparative analysis of the first stage of validation - steel sample (S235 steel), 3D analysis

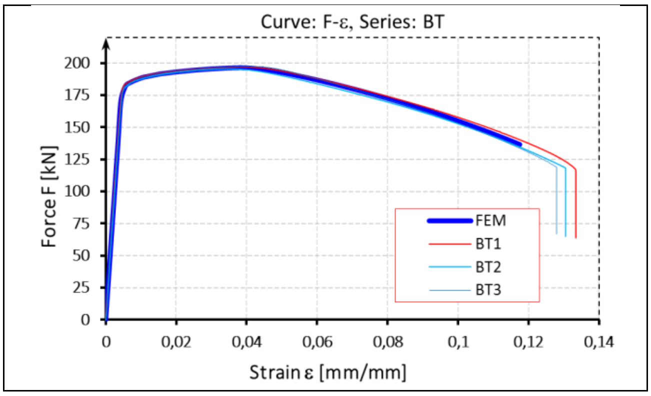

Fig. 3. Results of the FEM comparative analysis of the first stage of validation with results of the axial tensile test of the screw samples - class 10.9, 2D analysis

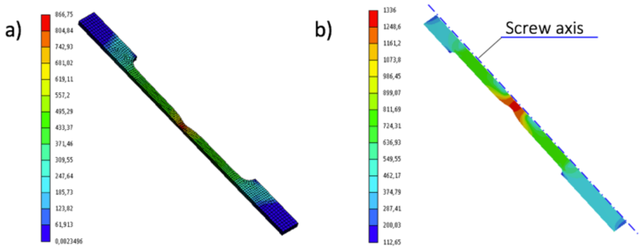

Fig. 4. The FEM model of the first validation stage: a) steel sample (3D model), b) screw sample - class 10.9 (2D analysis - radial symmetry)

In the three-dimensional FEM analysis of steel samples, double symmetry of the tested object was considered in relation to the surfaces intersecting its central axes (fig. 4a). In the FEM analysis of flat-head samples, flat models (fig. 4b) and three-dimensional models were used.

In the second stage of validation, a series of 11 axial tensile tests of the bolt-washer-nut was performed. The FEM analysis was carried out in the 2D (fig. 5a) and 3D version (fig. 5b).

The maximum value of force in the bolt, determined on the basis of laboratory tests, is: for samples SAF9 - 261.59 kN, for samples SAF10 - 263.18 kN, for samples SAF11 - 262.81 kN. These values are comparable to the force in the bolt defined in the FEM analysis: F_{FEM} = 264.37 kN (fig. 6).

The third stage consists in determining a comparative characteristic *F*-*Δ*, describing the deformation state of the butt joint, defined in the form of extended T-stubs (fig. 7). At this stage of the validation, a series of tests of axial stretching of T-stubs was carried out according to the following program:

- H01 series - connection made of HEA 240 (S235) profiles,
- B01 series - connection made of HEB 240 profiles (S355),
- SP01 series - connection made of sheet metal, face plate with a thickness t_p = 20 mm (S355),
- SP02 series - connection made of sheet metal, face plate with a thickness t_p = 12 mm (S235).

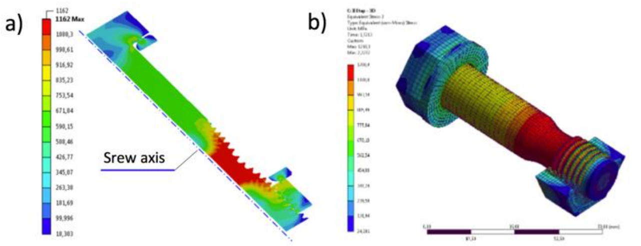

Fig. 5. FEM model of the second stage of validation: a) 2D analysis, b) 3D analysis

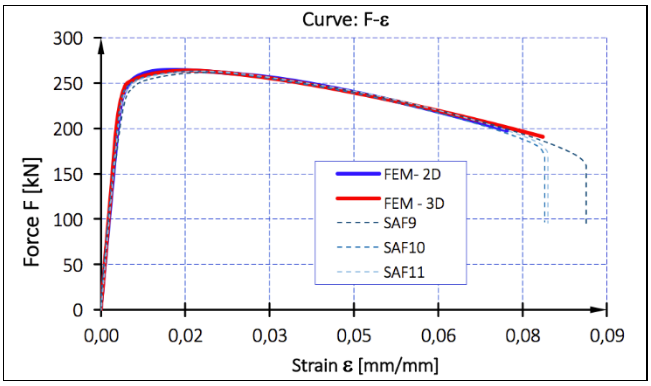

Fig. 6. Results of FEM comparative analysis of the second stage of validation with the results of axial tensile testing of bolts (Class 10.9 - ISO 4014)

a) b)

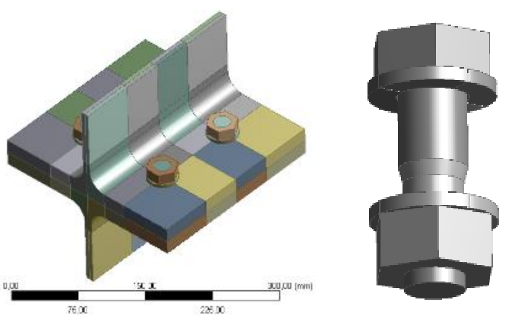

Fig. 7. FEM model of the third stage of validation: a) model of the T-stub, b) bolt model

In the numerical models of the objects studied, the geometry was mapped on the basis of the exact measurement of elements subjected to a tensile test.

At the last stage of hierarchical validation, the model of joining a beam to a post in a frame system was analyzed (fig. 8). The aim was to obtain convergent rotation angle results based on the analysis of the obtained characteristics *M-φ*. All components of the node were modeled using three-dimensional finite elements such as: Hex8, Tet4, Wed6 and Pyr5. Five layers of finite elements were adopted for the front plate and the column's shelf.

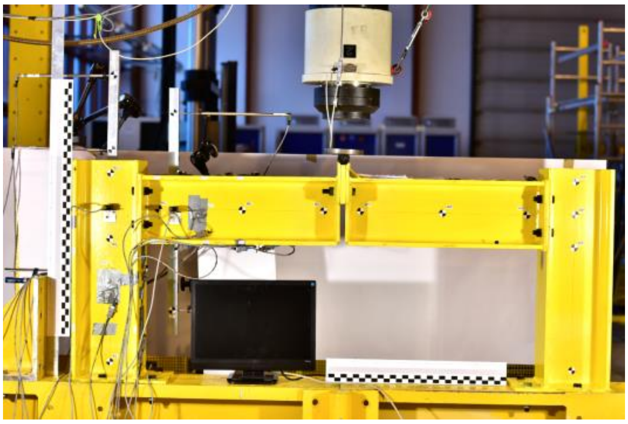

Fig. 8. Test stand for the fourth stage of validation - frame system made of HEB 260 profiles

The contact surfaces between the individual elements of the node were modeled as non-linear with a coefficient of friction of μ = 0.2 (accepted as for the surface in the natural state). The method of modeling contact surfaces between individual elements of the frame system, modeling the screw and grid discretization was analogous to that described in [1, 2]. In order to increase the efficiency of calculations, a half-frame system model was made using symmetry with respect to the center plane of the system.

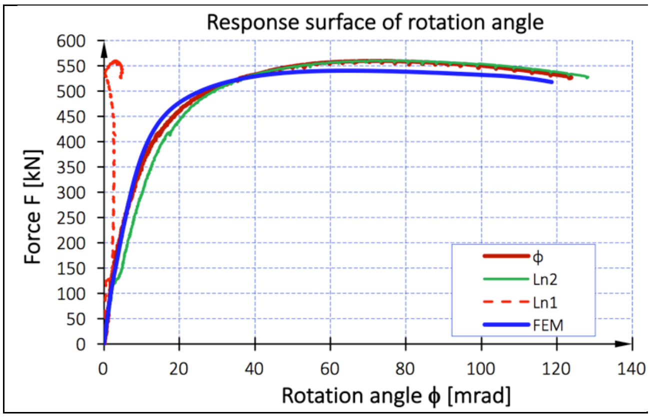

Fig. 9. Results of the FEM comparative analysis of the fourth stage of validation with results of the laboratory test. Measurement of the rotation angle with the use of inclinometers (Ln1 - inclinometer mounted on the column's web, Ln2 - inclinometer mounted on the web of the beam)

Fig. 9 presents comparison of the FEM analysis results with results of laboratory tests of a frame system made of HEB260 profiles. The reference criterion for the characteristics of *F-φ* was adopted as the reference point.

The obtained results fully confirm the credibility of the assumptions adopted at each stage of validation. The assumptions formulated in this way allow the use of the finite element method to forecast the rotational capability of steel structure nodes in various geometric configurations.

Rotation capacity of joints

Results of hierarchical validation of FEM models were used to develop a numerical experiment plan, on the basis of which an assessment of the impact of variable factors on the rotational capability of the node shown in fig. 10 is made.

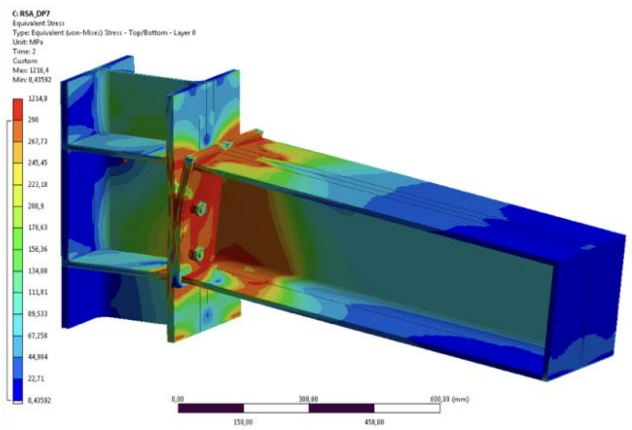

Fig. 10. FEM model of connection of a butt beam to a column

The following variables were taken into account in the analysis: h_b - height of the rafter profile, h_c - height of the column profile, t_p - panel thickness, w - horizontal bolt spacing, c_{g1} - distance from the axis of the upper bolt row to the upper surface of the rafter shelf. To determine the area of rotation angle response, a trivalent (-1, 0, 1) Hartley plan (PS/DS-P:Ha$_5$) was built on 27 systems, containing a combination of variable factors with the following ranges: t_p = 12÷20 mm, w = 135÷200 mm, c_{g1} = 60÷120 mm, h_b = 290÷490 mm and h_c = 300÷500 mm.

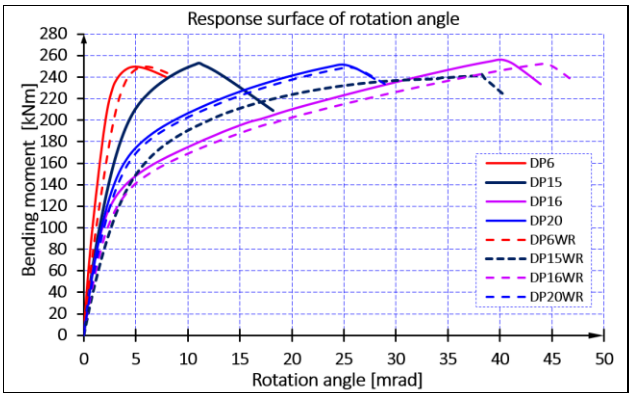

Fig. 11. Results of the numerical experiment plan: solid line - results for the system with ribs, dashed line - results for the system without ribs

In order to evaluate the effect of ribbing on the rotational ability, by analogy, calculations were made for the experiment plan of the node shown in fig. 10, but without stiffening ribs. Fig. 11 shows a comparative analysis of the results of selected experiment plan layouts.

Introduction to the analysis of relevant material characteristics, resulting from the multistage process of fine-tuning FEM models as part of hierarchical validation, is a prerequisite for obtaining reliable results of numerical analysis. The component method proposed in the standard [5] has not been fully developed yet in terms of forecasting the marketing capability, which prompts to look for other, alternative, but possibly reliable methods for estimating the marketing capacity of nodes in steel constructions.

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