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VALIDATION AND VERIFICATION PROCEDURES FOR CONNECTION DESIGN IN STEEL STRUCTURES

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Abstract. *The paper refers to aspects related to benchmark studies, validation and verification (V&V) of structural connections. The considerations emphasize questions encountered in the V&V process, principles of comparison of numerical results and experimental data, the importance of sensitivity study, new ideas regarding the relationship between the research and design finite element model, differences between the Component based model and the Design finite element model. The V&V is demonstrated on modelling of the T stub and on buckling of compressed stiffener.*

1 INTRODUCTION

1.1 Validation and Verification and Connection Design

In publications dealing with computational mechanics the authors express a need for V&V studies which could be used by code users and software developers, see [1]. However, there are different opinions on how such reference material should be developed, how complex problems should be considered, theoretical or with practical meaning, and if benchmark questions should refer only to analytical and numerical solutions or should also include experimental data. These inquiries are related to the differences between validation and verification. In the formal procedure called Validation and Verification, validation compares the numerical solution with the experimental data, whereas verification uses comparison of computational solutions with highly accurate (analytical or numerical) benchmark solutions. According to [2], code verification can be conducted through tests of agreement between a computational solution and four types of benchmark solutions: analytical, highly accurate numerical solutions, and manufactured solutions [3]. In contrast to numerical solutions used in the validation stage, the numerical solutions applied for verification can represent mathematical models with little physical importance. The verification on the analyst's side is based on the test of agreement with the known correct results, if such are available. Most of commercial codes, such as ANSYS, ABAQUS. see [4], and MIDAS support lists of well-documented benchmark tests. For example, ABAQUS in three manuals provides a wide variety of benchmark tests (including 93 NAFEMS benchmarks) from simple one-element tests to complex engineering problems and experiments (validation benchmarks). These example problems, containing input files, are advantageous for a user not only as material for verification but also as a great help in individual modelling, see [5] and [6]. Nevertheless, there is still lack of benchmark studies for some specific research areas such as, for example, connection design.
The design models of structural connections developed in last hundred year from interpolation and

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extrapolation of experimental results in tables and curve fitting models, see [7], to simple component based model (CBM), see [8] and advanced approaches for CBM [9] and [10]. The interpolation of experimental results is very safe procedure and was used for almost hundred years in structural steel and was replaced recently CBM. The curve fitting models has the only advantage in the simplicity of description in case of cyclic loading are still used in seismic design procedures. The major advantage of the component based models is the decomposition of the joint into components, which are well described based on engineering practice, as bolts, weld, compressed plated or by special the experiments. From this point of view is CBM taking the best historical solutions from the structural engineering in case of resistance, see [12], stiffness and deformation capacity of the structural steel connections. The simple CBM composes the final behaviour in one plane in terms of initial stiffness, ultimate resistance and deformation capacity. The extreme of such assembling is the model by one component only, see [13], which is very efficient in prediction of stiffness, where the accuracy is not necessary. It is also not surprisingly accurate for prediction of resistance in connections with one guiding component, as top angle or base plate. The advanced models are enable prediction of behaviour in 3M. The research finite elements models of structural connections were used for sensitivity studies from seventies. The question of reproduction of numerical simulation in the times of traditional calibrations procedures of major parameters were studied also at European scale, see [14]. The component the end plate in bending and the bolt in tension (or the column flange in bending and the bolt in tension) is one of the most complex part of the structural steel connections. Its component based model allow to take the prying forces into consideration. The complexity of FE modelling is deeply studied in last twenty years, see [15] and [16]. Later were commonly accepted the procedures to reach proper results in scientific oriented FE models and the strong limits for application of design FE models. Based on numerical experiments validated on experiments were developed behaviour of the well described and published components loaded by elevated temperature, as tying forces, moment normal interaction and torsion and of the new less described components, as backing channel. The fast development of the computer assisted design of steel and composite structures in field of complex structures, as plated structures in bridges, excavators and wind towers, glass structures and cold formed structures, clarified the design procedures in accuracy of models and its application in civil engineering. Today are CBM´s commonly supported by the Design finite element models (DFEM) not only to areas of design of hollow section connections. The design of this connections is still based on curve fitting models limited to only experimentally approved solutions. For connection of hollow sections of class 3 and 4 are available and used the DFEM. New generation advanced models was developed from simple tools, see [14], to Component based finite element model CBFEM, which are taken the advantages of both, finite elements assembly and plate modelling and the best engineering practice integrated into design of components, bolts, welds and compressed plates, with latest technology of design modelling and database based drawings.

The experimental data which can be used for validation should be treated separately and in a different way comparing to benchmark solutions applied for verification. The reasons for that are unavoidable errors and uncertainties associated with the result of experimental measurement. An error of a measurement (calculation) can be defined as the result of a measurement (calculation) minus the value of the measured (accurate solution), see [17]. As the accurate solution is usually unknown (eventually for simplified cases) the user can only deal with estimates of errors. Uncertainty can be thought of as a parameter associated with the result of a measurement (solution) that characterizes the dispersion of the values that could reasonably be attributed to the measured.

Experimental validation in the structural connections design through comparison between numerical results and experimental data obtained using the beam tests with for simple connections loaded in shear and cruciform tests for moment resistant connections loaded by bending moments are especially difficult and has limitations which are not economical, connection tests compare to most simple ones, but are due to inevitable uncertainties characterising the specimen behaviour. The limitations of experimental validation increase the importance of verification which is supposed to deliver evidence that mathematical models are properly implemented and that the numerical solution is correct with respect to the mathematical model.

1.2 Benchmark examples

Even though examples of experimental studies and examples of calculations following the Structural Eurocodes procedures are also useful and can be helpful for other users, here the term benchmark studies refers to computer simulations (numerical analysis). A well-developed benchmark example should satisfy the following requirements. The problem considered should be relatively simple, easy to understand. In authors' opinion for more complex problem less reliable solution can be provided. For complex problems, for example with actual material properties of steel or concrete, only numerical solutions can be obtained. Comparison among the numerical solutions obtained with the help of different software shows quite often unexpected discrepancy among the results as well. Even if the results are similar this should not be considered as a strong evidence of the solution's reliability. Two different numerical solutions can be only compared based on a solution sensitivity analysis.

Seeking for the simplicity we should accept that a considered case can show little of practical meaning. It is supposed to be used for verification of computational models not to solve an engineering problem. Critical is the material model taken into account. If the material models developed for actual structural materials are used, for example based on EC, with all required nonlinearities, only approximate solutions are possible and can substantially vary for different software. It is difficult to find a good balance between simplicity and a practical meaning of the chosen benchmark case. To solve this difficulty it is recommended to use in benchmark studies a hierarchical approach where a set of problems is considered, starting from simple cases with analytical solutions and then more complex problems, closer to the practice are investigated numerically. Such approach gives more confidence towards obtained solutions.

As a part of benchmark study the complete input data must be provided in the way easy to follow. All assumptions such as of material properties, boundary conditions, temperature distribution, loading conditions, large/small deformations and displacements must be clearly identified. For experimental examples all measurements and detailed description of the test procedure should be provided. For numerical benchmark examples mesh density study should also be conducted. It should be shown that provided results are within the range of asymptotic convergence. If possible the recommended solution should be given as the estimate of the asymptotic solution based on solutions for at least two succeeding mesh densities. For finite element calculations the complete procedures such as Grid Convergence Index (GCI), based on Richardson extrapolation, are recommended [18]. During the development of benchmark studies it also should be considered to check alternative numerical models. e. g. using different codes or solid vs. shell finite elements (if possible). Such approach increases the validity of the solution.

1.3 Numerical experiments

Parametric study is a desired element of the experimental work and an indispensable element of the numerical analysis. The cost needed to perform multiple experiments related to structural connections is usually small but a probabilistic distribution of the system response is rarely available. However, in the case of simulated benchmark problems computational cost of running multiple instances of a simple numerical experiment with varying input parameters is competitive.

The variance of a system response depends on the variance in the input parameters but also on the range at which it is tested. Nonlinearity of the response has to be taken into account as well when designing the benchmark tests. The numerical experiments should be performed out in the range where a reasonable variation in an input parameter causes a reasonable change in the system's response. Designing a benchmark test producing either a non-sensitive or overly sensitive response is undesirable. The sensitivity study for a system with multiple variable input parameters and multiple responses should be performed by regression analysis or variance based methods.

Actually selection of the System Response Quantity (SRQ), see [19], is important for both, verification and validation. However, in both cases it is subject to different limitations. In verification, SRQ means a quantity which describes the response of the structure and is selected for comparison with the value obtained from the benchmark solution. A user is less limited here as in the case of validation where the experimental data is always limited with the number of gauges and other instrumentation. The selection of the SRQ should reflect the main objective of the analysis and for structures in fires it usually refers to quantities describing heat transfer or mechanical response. For heat transfer problems temperatures obtained at the specific time instance at selected locations seems to be an optimal choice. For mechanical structural response usually we can choose between local and global (integral) quantities. Engineers are usually interested in stresses and internal forces, which are local quantities. They are subject to larger uncertainties especially in the case of validation. More appropriate are global quantities such as deflection which reflects deformation of the whole (or a large part of) structure and its boundary conditions

1.3 Experimental validation

As the experimental data is stochastic by nature and is always subject to some variation it should be actually defined by a probability distribution such. For complete comparison the numerical results should also be presented in analogous probabilistic manner using a probability distribution, generated by repeated calculations with some selected input data varying following prescribed distributions (so called probability simulations). Such extensive calculations can be conducted automatically with the help of specialised optimization packages (e.g. LS-OPT®, HyperStudy® or ModeFrontier®) which are more often included in nowadays commercial computational systems.

For many authors working on principles of validation and verification [1] the term calibration has negative meaning and describes a practice which should be avoided in numerical modelling. Calibration means here unjustified modification of the input data applied to a numerical model in order to shift the numerical results closer to the experimental data. An example of erroneous calibration is shown in Figure 1, where at the begging it is assumed that the numerical model well reflects the experiment however, due to some uncertainties associated with the experiment the first numerical prediction, differs from the first experimental result. Frequently in such cases the discrepancy between the experiment and the numerical simulation is attributable to some unidentified by the analyst input parameter and not to a limitation of the software and then through hiding one error by introducing another, the calibration process itself is erroneous. Calibration, applied for example through variation of material input data, shifts the result closer to the experimental response but at the same time changes the whole numerical model whose probability is now moved away from the experimental one. Due to the calibration, the new numerical model may easily show poorer predictive capability. This fact is principally revealed for modified input data (e.g. loading conditions).

There is a situation when the calibration process actually makes sense. If a full stochastic description of experimental data is known and probabilistic analysis was performed for the simulation and there is a difference between means of measured and simulated responses then calibration of physics models may be needed. The adjustment of the model introduces a change in the response that brings the entire spectrum of results closer to the experimental set of data. The calibration defined that way is much more complex process than just tweaking of the models and must be confirmed on different simulated events.

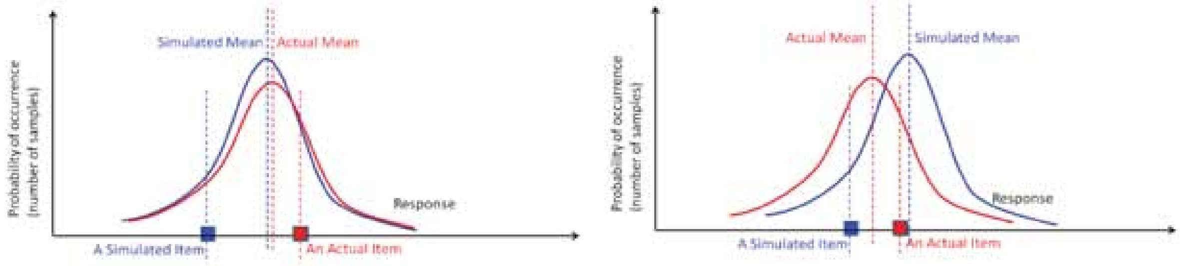

Figure 1: Example of calibration meaning unjustified shifting the numerical results closer to the experimental data, see [5]

2 VALIDATION OF REASERCH MODEL OF T STUB

2.1 Experiment

As very classical procedure is presented further a validation of T-stub with 2 bolts. Numerical model was validated according to results of two experiments performed on CTU Prague. MIDAS software was used for numerical simulation.

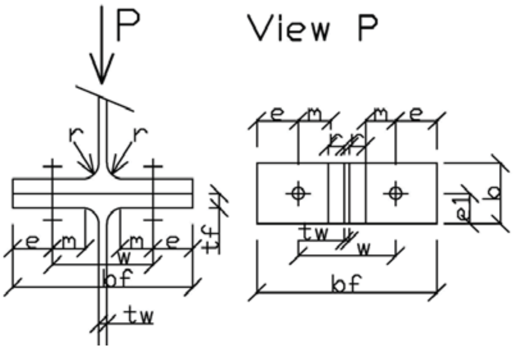

Figure 2: Geometry of T stub samples

Table 1: Measured geometry of T stubs, mm

Sample	Section	t_f	t_w	b_f	r	b	w	e_1	m	e	f_y	f_u	R
1	HEB 300	17,8	10,6	300	27,0	98,8	164	49,4	5,1	68,0	355	530	62 %
2	HEB 400	23,1	13,6	300	27,0	99,6	169	49,8	6,1	65,5	263	443	58 %

Two samples of T-stubs connected by two bolts M24 8.8 were designed and experimentally tested. T-stubs were performed by separating the upper flange of rolled HEB-sections. Dimensions of the samples are given in Figure 2 and Table 1. T-stub's webs were fixed to clamps and samples were subjected to tension force.

2.2 Material and Imperfections

Tensile tests of T-stubs material were performed, see Table 1 with yield stress f_y, ultimate stress f_u and deformation capacity R. The Multi-linear truth stress truth strain stress-strain diagram with statically determined values was used for material of T-stubs in numerical model. For the material of the bolts is considered a bilinear stress-strain diagram with strain hardening, Young´s modulus E = 210000 MPa, yield strength f_{yb} = 640 MPa and ultimate strength f_{ub} = 800 MPa. Maximal plastic strain is expected as ε_b = 5%.

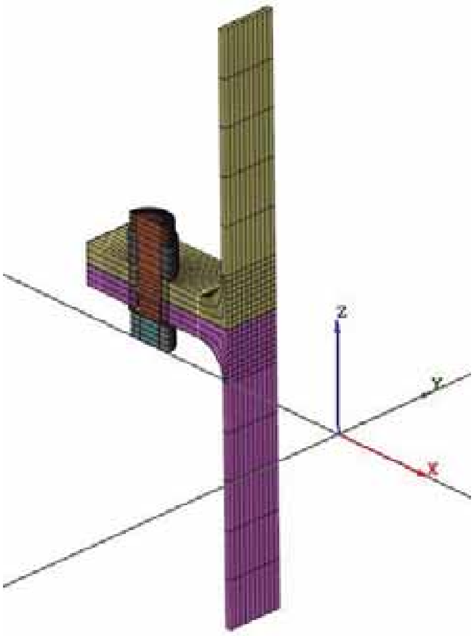

Figure 2: Numerical model of T sub

2.4 Validation procedure

Numerical model of the bolt was verified at the first step. Verification of the bolt numerical model was based on comparison with several analytical models and numerical model according to Wu et al [20]. Influence of the element size, number of elements through thickness of the flange, geometric imperfections, the choice of stress-strain diagrams and others were investigated as part of the validation process. Minimal three elements through flange thickness provide sufficient accuracy of numerical model. Element edge size 5 mm provides sufficient accuracy of calculation. It was found that only the thickness of the flange, bolts location and radius of curvature at the connection of the web to flange significantly affect results of numerical model. It is important to consider multilinear stress-strain diagram with static values for the material of T-stub.

Results obtained from validated numerical models are compared to experimental data. Comparisons of T-stub deformations are shown in Figure 3. It can be concluded that in both cases are numerical results very similar to the experiment. Comparisons of strains on the flange in plastic lines of bolt and plastic lines by web were done and similar conclusions have been reached.

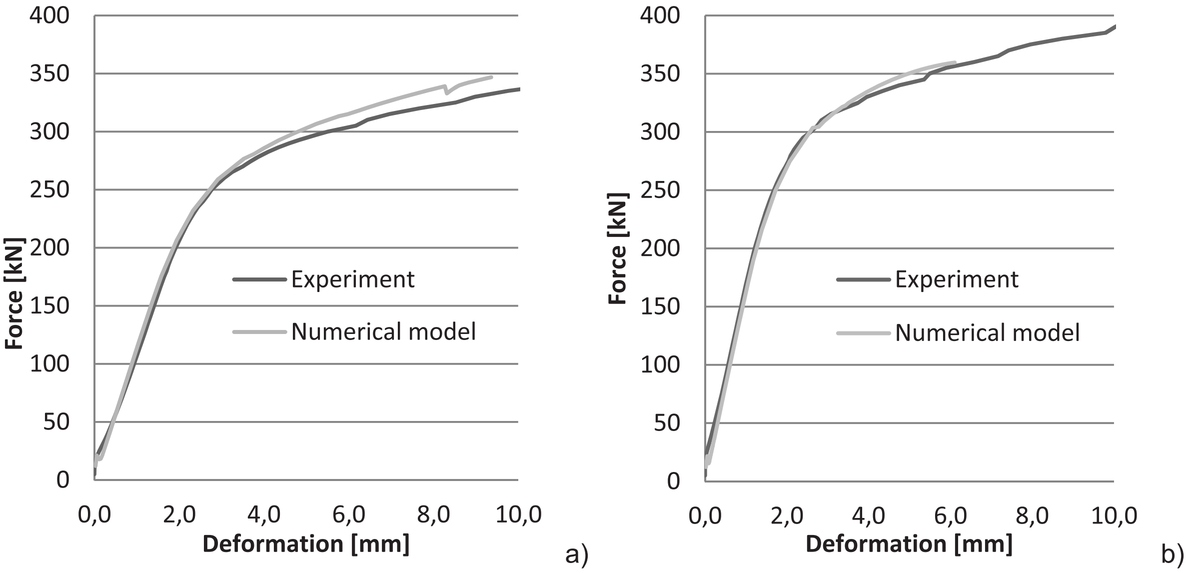

Figure 3: Force-deformation diagrams for T-stubs, a) sample HEB300, b) sample HEB400

3.1 VERIFICATION OF DESIGN MODEL OF COMPRESSED PLATE

3.1 Focus and geometry

In this part is presented a verification example of steel plate under uniform uniaxial compression with changing slenderness. The numerical results calculated in MIDAS are compared to reduction curve in Chapter 4 and Annex B, EN1993-1-5:2007 [21]. For each case is considered the same boundary conditions, material model and imperfections. A similar analysis using code ANSYS was published by Braun [22]. In the numerical analysis is used a square steel plate with dimensions *a* = *b* = 1000 mm and thickness changing from 7 mm to 30 mm.

3.2 Load cases and boundary conditions

The investigation is concentrated on a simple load case namely uniform uniaxial compression as shown in Figure 4. Boundary conditions are used hinged at all edges, the loaded edges are constrained in the y direction and unloaded are unconstrained.

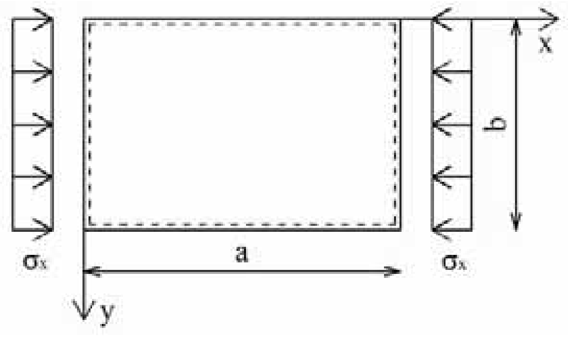

Figure 4: Load case and boundary conditions for verification example

3.3 Material model and imperfections

For the calculation is used isotropic material model to assure that mechanical behavior is same in all directions. The characteristic material properties of steel were utilized, Young´s modulus E = 210 000 MPa, Poissson´s ratio v = 0,3 and yield strength f_y = 355 MPa. The bilinear stress-strain curve with strain hardening was selected with maximal strain is ε = 5 % at ultimate strength f_u = 510 MPa as shown in Figure 5.

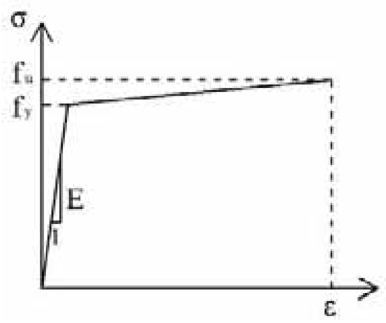

Figure 5: Material model for verification

Imperfections are modelled in the shape of first eigenmode coming from a linear bifurcation analysis (LBA) with amplitude recommended in Annex C, EN 1993-1-5 [21], i.e. a/200.

3.4 Numerical model

Plates are modelled using shell elements in MIDAS. The same material model, imperfections, loading and boundary conditions are considered as described previously. The load was applied only on one of the edges to assure symmetrical behavior. Supports were modelled in every node: constrained displacement degree of freedom in *z* direction at the unloaded edges, constrained displacement in y and z at the loaded edge, where is the stress load applied and constrained displacement in *x,y* and *z* at the loaded edge without the stress load. FE elements dimension is 100 x 100 mm as shown in Figure 6.

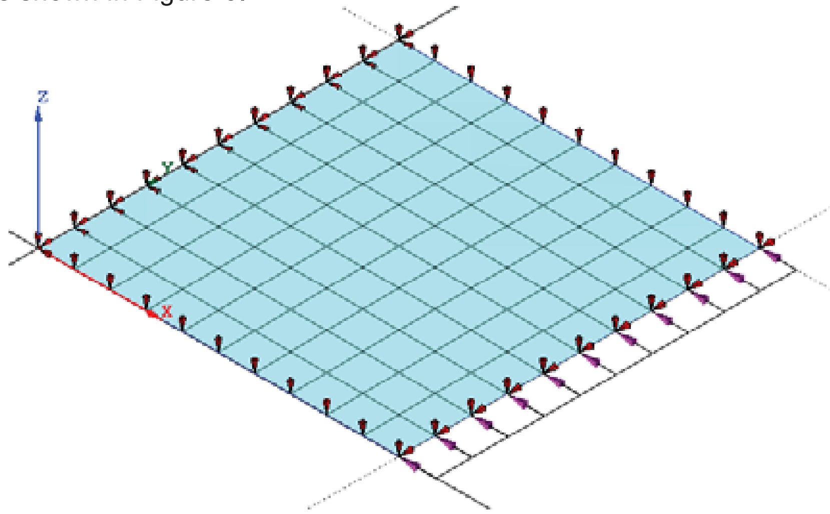

Figure 6: Numerical model

3.5 Verification on buckling curves

The reduction factor ρ depends on the boundary condition and slenderness and is chosen from EN 1993-1-5 section 4 or Annex B.

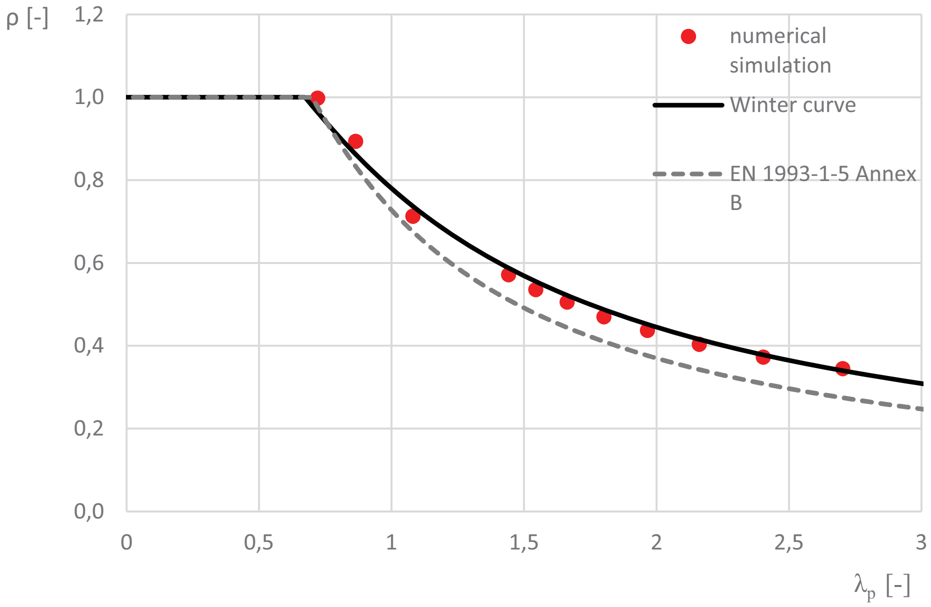

Figure 7: Buckling curves and numerical simulations

The reduction factor according to Chapter 4 for may be determined:

$$\rho = 1{,}0 \text{ for } \bar{\lambda}_p \le 0{,}673 \tag{1}$$

$$\rho = \frac{\bar{\lambda}_p - 0{,}055(3+\psi)}{\bar{\lambda}_p^2} \text{ for } \bar{\lambda}_p > 0{,}673 \tag{2}$$

The reduction factor according to Annex B is determined:

$$\rho = \frac{1}{\phi_p + \sqrt{\phi_p^2 - \bar{\lambda}_p}} \tag{3}$$

where $\bar{\lambda}_p$ is the modified plate slenderness,

$$\phi_p = \frac{1}{2}\left(1 + \alpha_p\left(\bar{\lambda}_p - \bar{\lambda}_{p0}\right) + \bar{\lambda}_p\right) \tag{4}$$

where α_p is 0,13 for hot rolled and 0,34 for welded or cold formed sections, $\bar{\lambda}_{p0}$ is 0,7 for direct stress and 0,8 for shear and transverse stress buckling mode.

Results from numerical simulation are shown in Figure 7. It can be concluded that in all cases are numerical results very similar to the Winter curve. The numerical study could be further extended by FE mesh density investigation and influence of different boundary conditions.

4 CONCLUSIONS

Four decades ago computational analysis of structural connection was treated by some researchers as a non-scientific matter. Two decades later it was already a widely accepted addition or even extension of experimental and theoretical work, see [24]. Today computational analysis, in particular computational mechanics and fluid dynamics, is commonly used as an indispensable design tool and a catalyst of many relevant research fields. The recommendation for design by advanced modelling in structural steel is already hidden but ready to be used in Chapter 5 and Annex C of EN 1993-1-5:2005 [21]. Development of modern general-purpose software and decreasing cost of computational resources facilitate this trend. As the computational tools become more readily available and easier to use, even to relatively inexperienced engineers, more scepticism and scrutiny should to be employed when judging one's computational analysis. The only way to prove correctness of simulated results is through a methodical verification and validation process. Without it the analysis is meaningless and cannot be used for making any decisions. In the case when the analysed event is too complex or overly expensive to test experimentally, hierarchical validation is recommended, see [25].

However for structural connections with thousands experiments available the validation process may be executed. But even in such situation the verification process performed through benchmark tests gains crucial importance. Seeing the need of making the results of research more transparent to the public, the office of science and technology policy in the United States issued a memorandum stipulating increased access to the results of federally funded scientific research, see [26]. Such data can be easily verified or used for verification (or benchmarking), of some other work. The trend of making extended data available together with a report or publication persists in order to build confidence in growing number of performed numerical simulations. To achieve this goal it seems even more beneficial at this point to develop a standard set of smaller benchmark tests that can be used as a reference in the verification process of simulations, see [24]. The source and the extent of such benchmark tests for the field of structural connections is yet to be established.

ANNOUNCEMENT

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REFERENCES

[1] Kwasniewski L., Numerical verification of post-critical Beck's column behavior, *International Journal of Non-Linear Mechanics,* 45 (3), 2010, 242-255.

[2] AIAA, Guide for the Verification and Validation of Computational Fluid Dynamics Simulations, American Institute of Aeronautics and Astronautics, AIAA-G-077-1998, Reston, VA, 1998.

[3] Oberkampf W.L., Trucano T.G., Verification and validation benchmarks, Nuclear Engineering and Design 238, 2008, 716–743.

[4] SIMULIA, Abaqus 6.11 Benchmarks Manual, © Dassault Systèmes, 2011.

[5] Wald F., Burgess I., Kwasniewski L., Horová K, Caldová E., *Benchmark studies, Experimental validation of numerical models in fire engineering*, CTU Publishing House, 2014, 198 p., ISBN 9788001054437.

[6] Wald F., Burgess I., Kwasniewski L., Horová K., Caldová, E., *Benchmark studies, Verification of numerical models in fire engineering*. CTU Publishing House, 2014. 328 p., ISBN 9788001054420.

[7] Chen, W.F., Abdalla K.M., Expanded database of semi-rigid steel connections, Computers and Structures, 56, (4), 1995, 553-564.

[8] EN 1993-1-8, Eurocode 3, Design of steel structures, Part 1-8, Design of Joints, CEN, Brussels 2005.

[9] da Silva L. S, Towards a consistent design approach for steel joints under generalized loading, *Journal of Constructional Steel Research,* 64 (2008) 1059–1075.

[10] Block FM, Davison JB, Burgess IW & Plank RJ, Deformation-reversal in component-based connection elements for analysis of steel frames in fire. *Journal of Constructional Steel Research*, 86, 2013, 54-65.

[11] Zoetemeijer, P.: *Summary of the Researches on Bolted Beam-to-Column Connections*. Report 6-85-7, University of Technology, Delft 1985.

[12] Steenhuis M., Gresnigt N., Weynand K., *Pre-Design of Semi-Rigid Joints Ii Steel Frames*, Proceedings of the Second State of the Art Workshop on Semi-Rigid Behaviour of Civil Engineering Structural Connections, COST C1, Prague, 1994, 131-140.

[13] Agerskov, H.: *High-strength bolted connections subject to prying*, Journal of Structural Division, ASCE, 102 (1), 1976, 161-175.

[14] Virdi K. S. et al, *Numerical Simulation of Semi Rigid Connections by the Finite Element Method*, Report of Working Group 6 Numerical, Simulation COST C1, Brussels Luxembourg, 1999.

[15] Bursi O. S., Jaspart J. P., Benchmarks for Finite Element Modelling of Bolted Steel

Connections*, Journal of Constructional Steel Research,* 43 (1-3), 1997, 17-42.

[16] Brito P. H., Rocha C.R., Filho F.C., Martins E., Rubira C.M.F., A Method for Modeling and Testing Exceptions in Component-Based Software Development, Dependable Computing, Lecture Notes in Computer Science, 3747, 2005, 61-79.

[17] ISO, Guide to the Expression of Uncertainty in Measurement, ISO Geneva, 1993.

[18] Roache P.J., Verification and Validation in Computational Science and Engineering, Computing in Science Engineering, Hermosa Publishers, 1998.

[19] Kwasniewski L., Nonlinear dynamic simulations of progressive collapse for a multistory building *Engineering Structures*, 32 (5), 2010, 1223-1235.

[20] Wu, Z., Zhang, S. and Jiang, S., *Simulation of tensile bolts in finite element modeling of semi-rigid beam-to-column connections*, International Journal of Steel Structures, Vol. 12, No. 3, pp. 339-350, 2012.

[21] EN 1993-1-5*, Eurocode 3: Design of steel structures - Part 1-5: Plated Structural Elements,* CEN, Brussels, 2007.

[22] Braun B., *Stability of steel plates under combined loading*, Institut für Konstruktion und Entwurf, Stuttgart, 2010.

[23] Jetteur P., Cescotto S. *A mixed finite element for the analysis of large inelastic strains*, International Journal for Numerical Methods in Engineering, 31, 1991, 229-239.

[24] NAFEMS, National Agency for Finite Element Methods, http://www.nafems.org/, 2013.

[25] ASME Guide for Verification and Validation in Computational Solid Mechanics, The American Society of Mechanical Engineers, ISBN 079183042X, 2006.

[26] Holdren J. P., Increasing Access to the Results of Federally Funded Scientific Research, Memorandum for the Heads of Executive Departments and Agencies, Office of Science and Technology Policy, Washington, D.C, 2013.