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Focussed on Modelling in Mechanics

Experiment and numerical modeling suspended ceiling with identification of working diagram material

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ABSTRACT. The aim of this topic is to describe creating of working diagrams of structural materials. These will be used as input parameters for nonlinear analysis of real structures. Working diagrams of construction material are derived from experimental tensile tests and numerical analysis. We will use construction steel in this case. Derived working diagrams are used as an input parameter for numerical modelling of real structures. They are also used as a comparison with data from realized physical tests. Numerical modelling is based on 3D model of structure and it takes into account physical and geometrical nonlinearities.

KEYWORDS. Experiment; Numerical modelling; Working diagrams; Analysis; Finite element method.

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INTRODUCTION

Design of steel structures is done according to standard EC and recommendations [1]. These methods are accurate for global analysis of construction and also for design of its structural parts. Nowadays advanced methods for assessment of civil constructions are using. These methods with usage of experimental measuring are based on sophisticated numerical analysis. This article describes process of creating working diagrams of steel in detail [2]. Afterwards input data are used for analysis of construction of suspended ceiling [3].

Currently method of finite elements is mostly used for numerical analysis of civil structures [4] and mainly for steel constructions [5, 6]. Finite element methods can appropriately take into account different nonlinearities [7, 8]. One of new methods used for solution of resistance of steel connections is for example CBFEM [9]. This method extends component method and uses FE method. These methods are easily implemented to calculation software for civil engineering. There are disadvantages. Users have to know background of these methods as well as their possibilities and more detailed input data (e.g. material models, real working diagrams).

STEEL SUSPENDED CEILING

While solving construction of steel suspended ceiling a special approach was required. Therefore this research was created to deal with construction for clean areas for example pharmaceutical and chemical laboratories, paint shops in industrial areas etc. Special approach was required for service and technological loads. Ceiling has to be walkable to allow service load and to have maintainable conduits such as ventilation and electrical wiring. Other requirements were heat and sound insulations. EC standards cannot be used in case of these requirements [10]. Therefore 3D model and stress-strain evaluation were used for design.

Numerical analysis takes physical and geometrical nonlinearities into account and is in accordance with EC [11, 12] and [13]. Physical experiment was made to check design of real structures and deflections and to validate calculation process.

Suspended panel ceiling consists of connected sandwich panels which are hung on construction by rods. This is a development of method presented in [3], but working diagrams are not used there. Considered loads acting on a cassette are: Surface load 1.00 kN/m^2 and point loads 4x1.00 kN (max. area 10 m^2). Internal suction is not considered in this case. However extreme value of internal pressure (300 Pa) is considered in short term. Dimensions of panel are 1200x2300x82mm. Sandwich panel consists of three main components as shown in the Fig. 1 on left. Bearing part is made from steel plate cassettes (thickness 0.80 mm), two symmetrical thin walled C profiles which are placed between the cassettes and the last component is non-bearing and it is made from mineral wool insulation.

Figure 1: Detail of panel of suspended ceiling (left) suspended ceiling with surface load and 6x point load (right).

Minimal yield strength of steel is considered 235MPa. Panels are supported by L profiles which are connected by steel buckles and Z clips. These clips are suspended on main construction by rods Ø10 mm S235. L profiles are from steel S235 as well. Sandwich panels are fixed to L profiles by screws.

Part of construction is manufactured to check the functionality of design. Model consists of 4 panels and 6 rods suspended on main steel structure. Total dimensions are approximately 2350x4800mm. Overview of model is in the Fig. 1 (on the right). Working diagrams of steel were made from samples made from materials used in model.

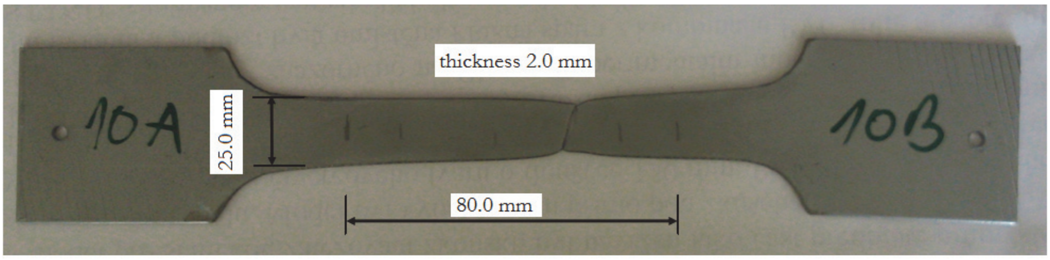


Figure 2: Steel samples.

EXPERIMENTAL MEASUREMENT OF SAMPLES AND NUMERICAL EVALUATION

Testing of material properties of steel is a wide area. Verified procedures are still being developed, especially effect of temperature and special conditions of testing [14-16]. 6 tensile tests of steel samples (S235) were made during physical experiments. Loads and longitudinal deformations were evaluated during tests. Longitudinal deformations were measured by move of a head of a press. Tests were done according to procedures [17] and [18] and on standardized samples. Typical sample of steel after the test is shown in the Fig. 2.

Tensile working diagram from 6 laboratory tests is shown as a solid line in the Fig. 3. Final numerical result is shown as a dashed line. All samples were loaded until they broke. The average strength steel f_u from test is 409.8Mpa. The standard deviation of static file is 2.3 MPa. In [19] and [20] are desribed in detail information about testing of material properties. Articles also includes the results of a large number of tests. Results of the tensile tests and the results from published works for steel S235 are similar also. Strength of the steel from the tensile tests f_u and published results are slightly lower compared with the published results. Steel meets declared value of producer.

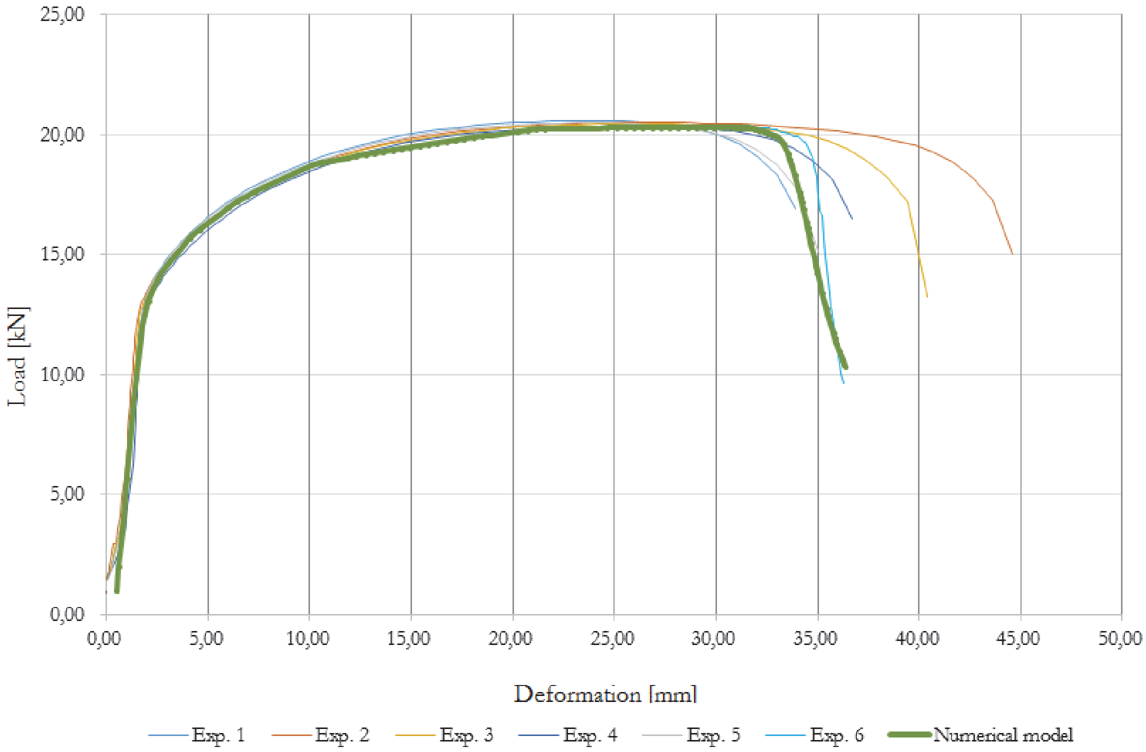
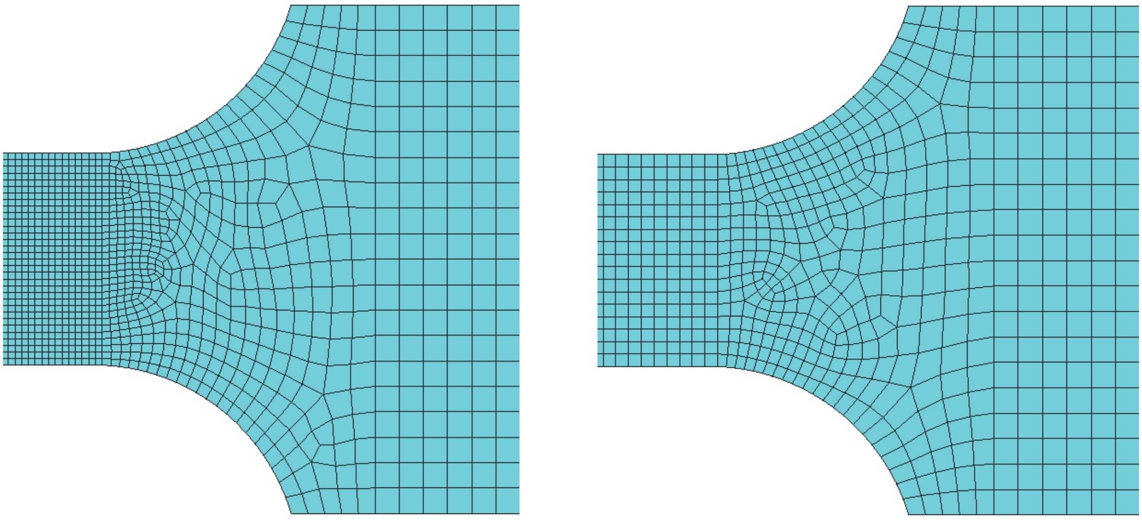


Figure 3: Tensile working diagrams of steel – laboratory test.

Performed tensile tests were modelled in ANSYS 16 [21] afterwards. 20-nodes finite element SOLID186 was used for nonlinear numerical model capable of collaps state evaluation as indicated on Fig. 3. Mesh of finite elements of a sample is in the Fig. 4. Three sizes of finite elements were made to proof influence on results. Sizes were from 0.75 to 3.00mm. It was found out that size of elements does not have influence on results. The size of 1.50mm was chosen as a optimum variant. In numerical model are 7300 finite elements and 40510 nodes. Method Newton-Raphson was used for solution of nonlinear equations of system. CP algorithm was used for boundary conditions in the fixing of the press. Afterwards the load was brought to the sample by displacement of one main node. Size of load step was varied in the interval from 1/2000 to 1/80 of the prescribed deformation. The total prescribed deformation is 35 mm. Slip of the press was simulated by changing the stiffness of working diagram.

Multilinear working diagram was chosen to create numerical model. The multilinear working diagram corresponds with working diagram of structural steel taken from [11]. The used material diagram was gradually modified to correspond to shape of behaviour of real sample during tensile test. Final shape of multilinear material diagram in the Fig. 5 was acquired by iteration. While using multilinear material diagram physical experiment results corresponded to numerical analysis. Elastic material diagram with linear hardening is possible to derive from multilinear material diagram.



Fine mesh size - 0.75 mm

Typical mesh size - 1.5 mm

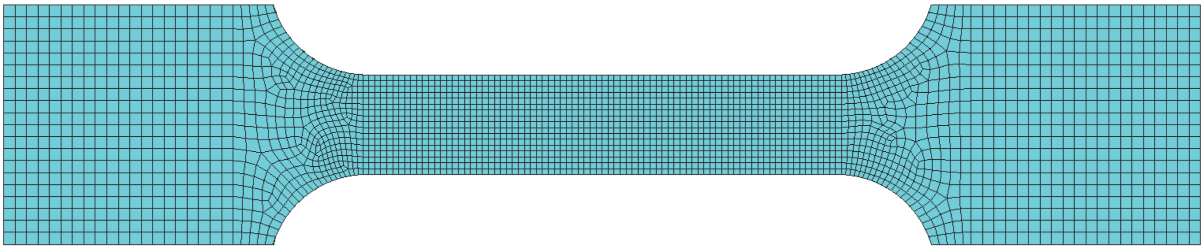


Figure 4: Numerical model of a sample with typical mesh.

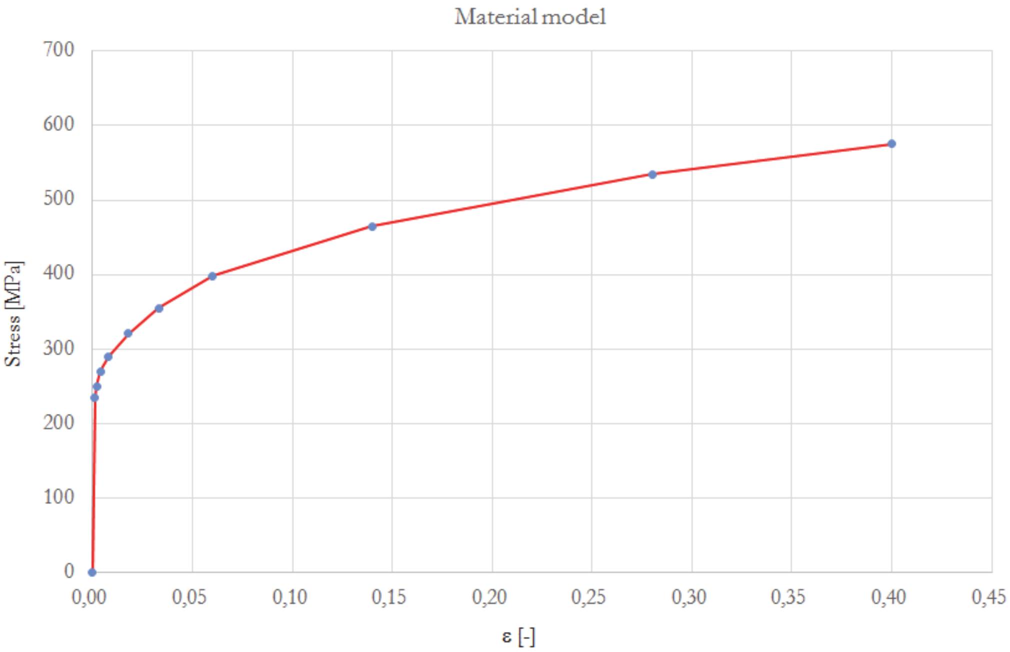


Figure 5: Material diagram of steel.

Maximal von Mises stress in deformed model is shown in the Fig. 6. This case is for critical force. Concentration of stress in numerical model corresponds with real deformation of sample, see Fig. 2.

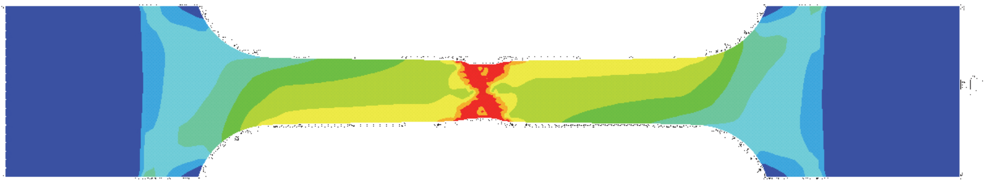


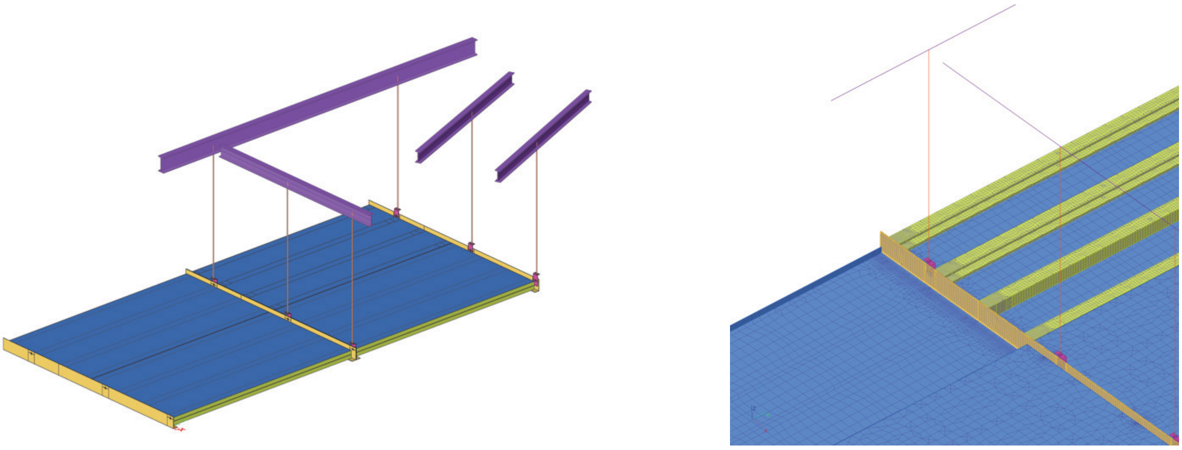
Figure 6: Numerical model - stress.

MODEL OF SUSPENDED CEILING AND LOADING TEST

3D computational model from shell and beam finite elements was made for static analysis of sandwich suspended ceiling. Software Scia Engineer 2015 [22] and ANSYS 16 [21] were used for calculation. Complete overview of model of suspended ceiling and of chosen panel PN1 is in the Fig. 7. With respect to time saving the model in ANSYS 16 [21] includes only the chosen panel PN1.

Loading test made on manufactured sample was done for check of correctness of numerical models. Vertical deflections were measured during physical test in chosen places of suspended ceiling. Deformations were measured by extensometer and with use of a datalogger Ahlborn ALMEMO 2690 and a computer.

The measurement was done using four extensometers with range 0 to 25mm. Record of measuring was continual with interval of one second. Numerical results were compared with data from extensometers placed in centre of cassette PN1.



Scia Engineer

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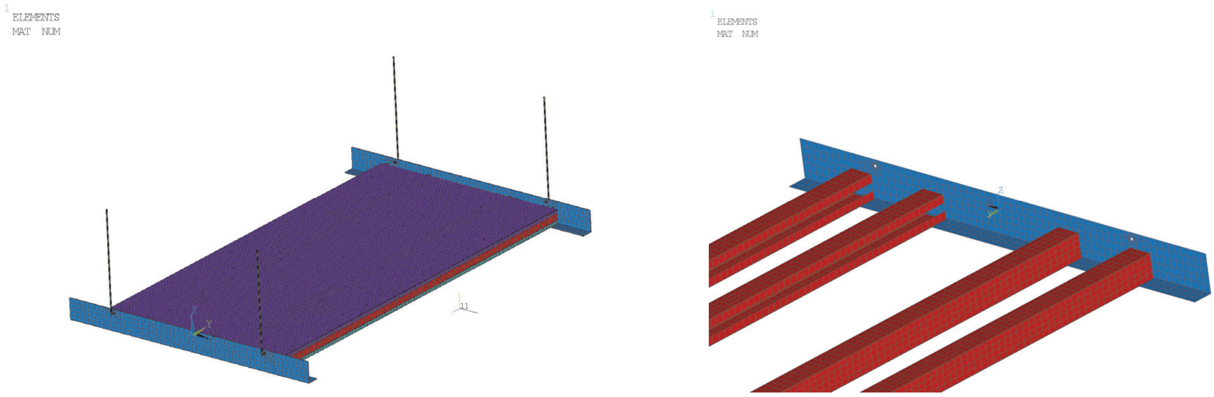


ANSYS

ANSYS

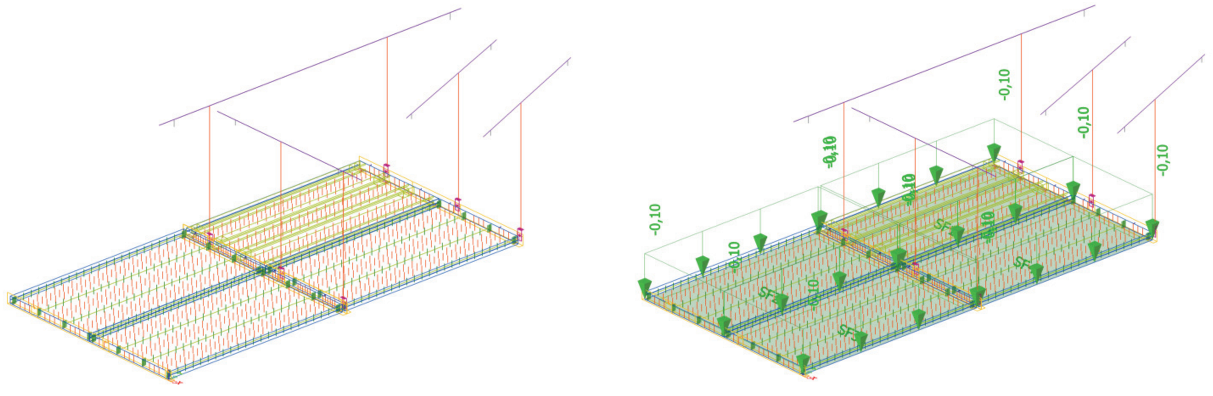
Figure 7: Computational model of suspended ceiling and selected details.

Three extensometers are placed diagonally on panel PN1. Finite element mesh was refined in the numerical model. Refined mesh was used for better results on measured panel and for better stress distribution on elements and their values. Refined mesh can be seen in the Fig. 7 (right). Refined mesh was used only on selected panel with respect to time saving. Numerical model in Scia Engineer had 359 526 degrees of freedom and model was created from shell and beam elements. Both types of finite elements had 6 DOF (3 translational and 3 rotational). Structural nonlinearities and friction were respected in numerical model. Structural nonlinearities were considered for screws and rods connections. These elements were considered only in tension. Steel material was considered elastic-plastic with linear hardening in Scia Engineer [22] and therefore physical nonlinearity was taken into account. Modified Newton-Rhapson method was chosen to solve nonlinear system of equations. Calculation ran in 40 loading steps. The same approach was used for system ANSYS but in ANSYS multilinear working diagram of steel was used.

Design and check of suspended sandwich ceiling was done for 10 load cases. Load case LC1 is self-weight and it was generated automatically. Other load cases are surface loads LC2 which represented weight of insulation. LC3 represented technological load 1.00 kN/m^2 (one cassette) and LC4 (four cassettes). Load case LC5 was point load. Load cases LC6 - LC10 represented walkability of the ceiling, specifically LC6 represented 6 forces each of 1.00 kN. This load case caused by people was used for comparison with physical test. This case should not happen but it was selected as an extreme case of service load. Combination of load cases LC7+LC8+LC9+LC10 represented situation when people walk on ceiling. It was specifically represented by 4 forces each of 1.00kN. Forces acted on area 50x50mm. These load cases are used for service combinations. Load cases with their appropriate coefficients mentioned above were used for nonlinear combinations. Some of these combinations were created according to investor and normative procedures.

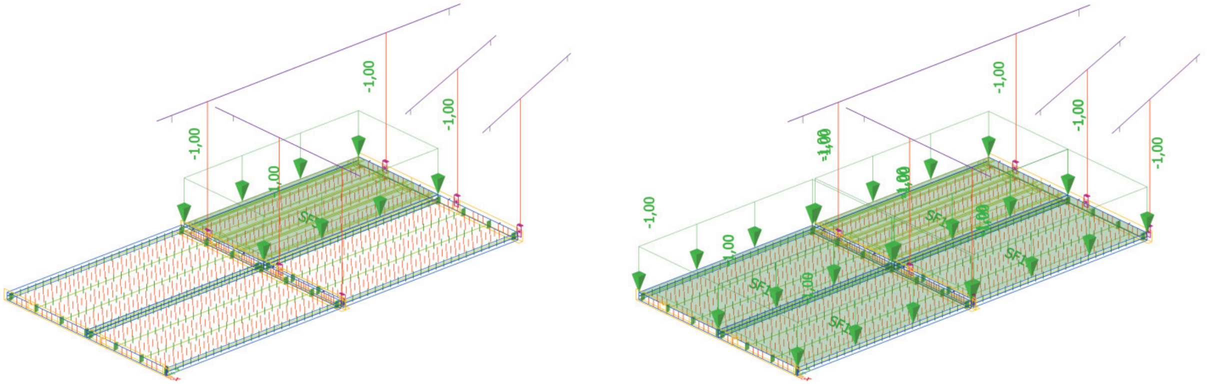
All loads were defined with characteristic values. Appropriate coefficients were used for load cases in each combination. Load coefficients were chosen according to physical test and according to combinations for dead and variable loads.

Stresses, strains and deformations were used to check each component of the ceiling [11-13]. Construction satisfies checks if principle surface strain is lower than 5%. It is recommended to reduce principal plastic strain by 0.2% for reduction of membrane deformation. Checked parts of suspended ceiling were: steel cassette plate, reinforcing C profile, bearing L profile, rod, Z clip and screws. Selected graphical outputs for structural parts of sandwich ceiling are shown as von Mises stresses in the Fig. 9. Full plasticity is reached only in small areas and chosen material model is conservative. Allowable strains are fulfilled.



LC1 – self-weight

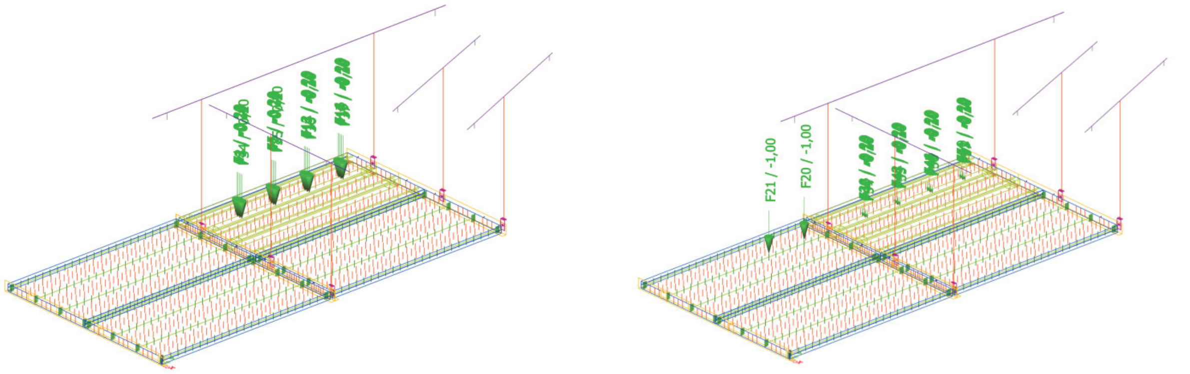
LC2 – insulation 0.10 kN/m^2



LC3 – technology (test) 1.0 kN/m^2

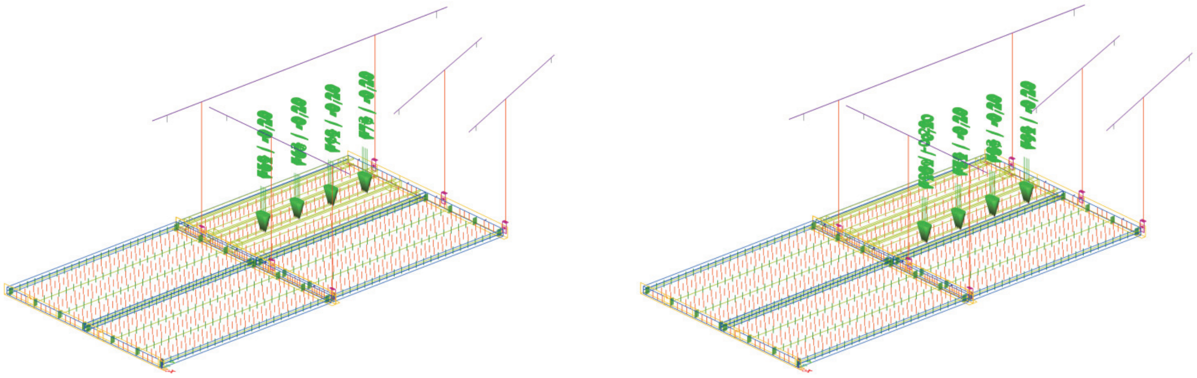
LC4 – technology (working) 1.00 kN/m^2

Figure 8: Load and Computational models



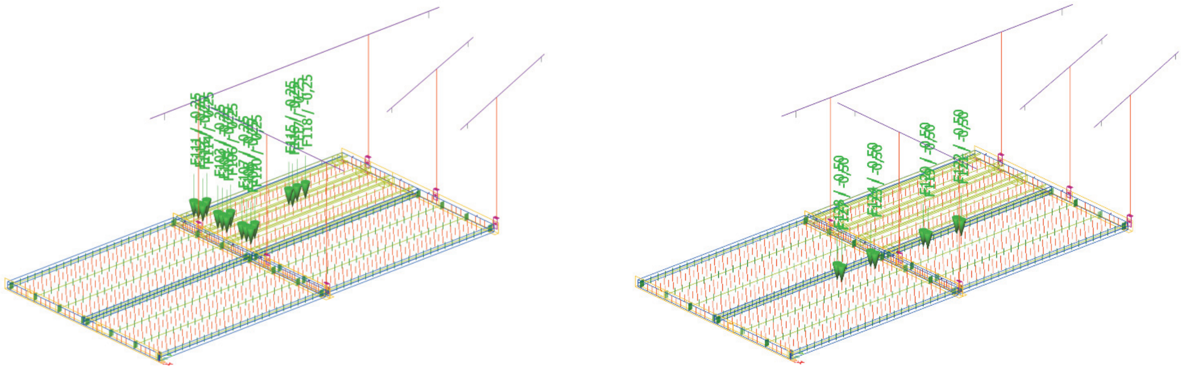
LC5 – service load (test) 1.0 kN 4x

LC6 – service load (test) 1.0 kN 6x



LC7 – service load (a) 1.0kN 4x

LC8 – service load (b) 1.00kN 4x



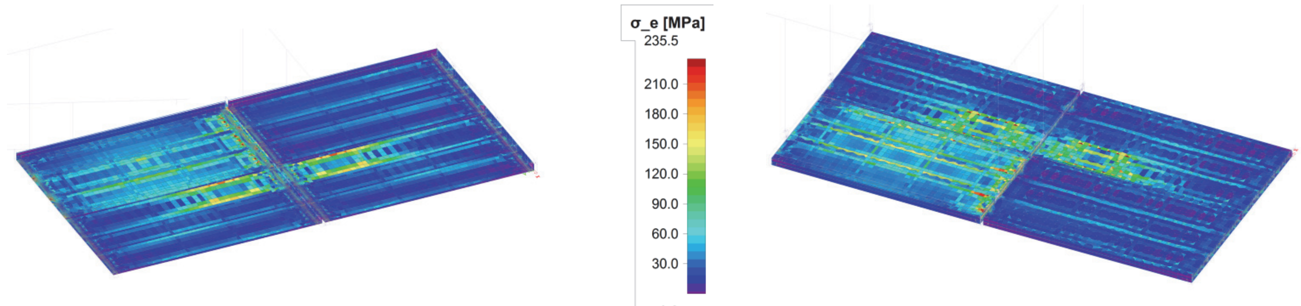
LC9 – service load (c) 1.0kN 4x

LC10 – service load (d) 1.0kN 4x

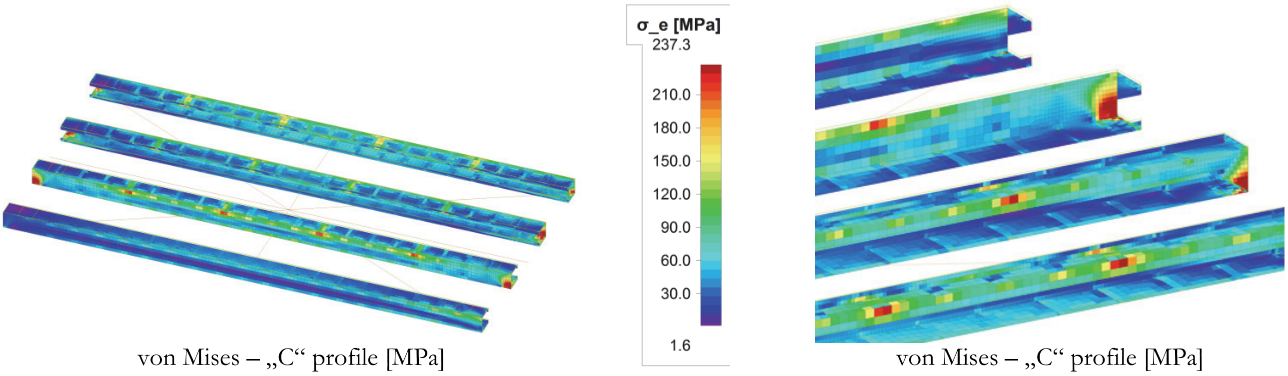
Figure 8 (continuation): Load and Computational models.

Mentioned structural parts satisfied requirements for critical nonlinear combination. Physical load tests of suspended ceiling shown in the Fig. 2 were used to check behaviour of numerical model. Critical nonlinear combination was combination NC3. This combination included self-weight of construction, surface loads and 6-point forces. Surface vertical deformation Uz is shown in the Fig. 10. Maximal value of deformation Uz was 13.10 mm. This deformation was designated as a comparison to real behaviour of construction. Structure compared to numerical model had similar behaviour and deformation to loads. Influence of loading of each steel cassette is evident according to mentioned pictures.

Values of vertical deformations in place of diagonal in the Fig. 11 are shown for specific loading step. Shown value represents placement of sensor in the middle of the cassette. Calculated value corresponds to measured deformation 14.60mm.



von Mises – panel [[MPa] von Mises – panel [MPa]



von Mises – „C“ profile [MPa] von Mises – „C“ profile [MPa]

Figure 9: von Mises stress [MPa].

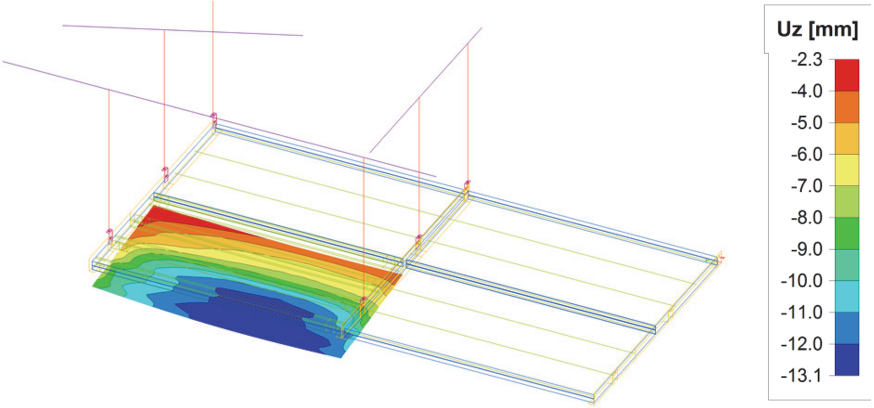


Figure 10: Deformations – Uz [mm]

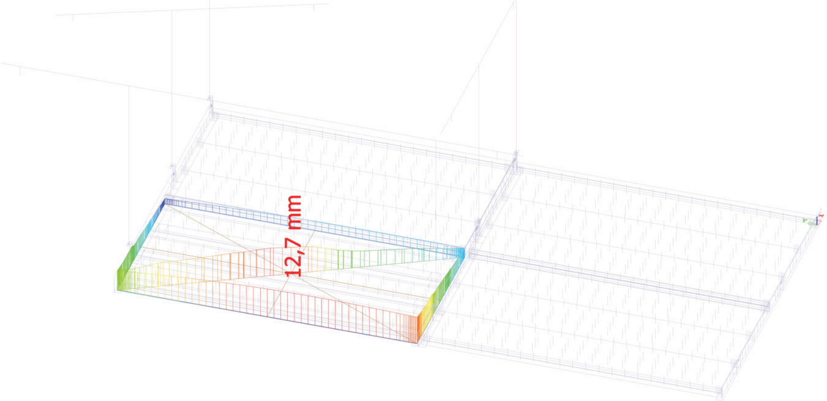


Figure 11: Transverse Deformations – Uz [mm]

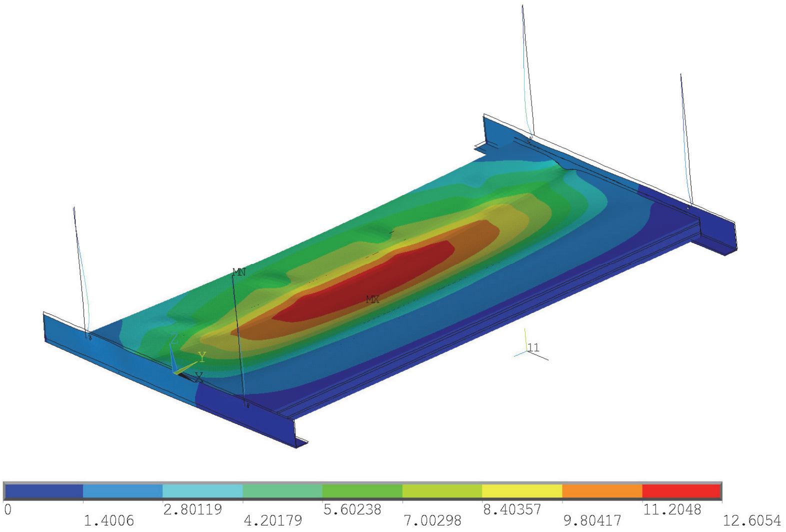


Figure 12: Deformations ANSYS Uz [mm].

Other calculations were done in ANSYS 16 [21] where multilinear working diagram of steel was used. Case when only 4 forces and surface load acted on cassette were solved in ANSYS 16. Final values of deformation are shown in the Fig. 12. Deflection 12.90 mm was measured during physical test. Results from numerical models and from physical test were in good conformity. Therefore the numerical models are considered to be appropriate according to deformations, internal forces and stresses.

CONCLUSIONS

Article presents design and analysis of developed suspended ceiling intended for clean areas as a special construction. Analysis of construction and numerical modelling is using derived material diagrams from tensile test for better results. Working diagrams of loading depending on changing of cross-section were used for more accurate working diagram of steel. Real working diagram of steel was used as a foundation for creation of multilinear material model for ANSYS. Nonlinear numerical model of tensile test with ability to identify collapse of the investigate members was also created to validate this material model. The results show that numerical model of tensile test with use of multilinear material model greatly corresponds to physical experiment. The test corresponds according to stiffness and stresses and also to longitudinal and transversal deformations. General procedure of design is chosen according to specific functional properties of suspended ceiling which do not allow normative procedure. This general procedure uses stress-strain analysis for steel structures. Selected procedure design with the use of 3D computational model and FEM allows economical and effective design of construction. Loading test which corresponded to numerical modelling of suspended ceiling was done to check executed procedures. Final values of deformations and strains from numerical models and from physical test were in good conformity. Appropriate nonlinearities in calculation had to be considered to model real behaviour. Geometrical nonlinearity had a great impact to internal forces. These structural nonlinearities were for example use of a contact surfaces and friction. Multilinear working diagram and elastic-plastic material with linear hardening was used for physical nonlinearity. Differences in results are although insignificantly small for specific area in which numerical modelling and loading test was done.

The consideration of the effect of nonlinearities is always necessary in case of advanced analysis. Total load capacity of structure is reduced when considering geometric nonlinearities in the calculation. Solved construction is a typical example. Effect of geometric nonlinearity is more pronounced than the effect of physical nonlinearity on subtle steel structures. Bearing capacity is increased taking into account the physical non-linearity. Deformation of the structure increases typically. Therefore it is necessary to pay attention to the correct selection of criteria for serviceability limit state. Design standards specify criteria for nonlinear analysis of steel structures and the use of plasticity is limited by codes to a safe level. Using advanced analysis taking into account nonlinearities with combined with FEM model allows to solve challenging construction tasks.

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