Numerical validation of selected computer programs in nonlinear analysis of steel frame exposed to fire

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Abstract

Validation of the fire resistance estimate obtained for the same steel frame bearing structure using two different computational models, i.e. one using bar elements in the SAFIR environment and another one using 3D brick elements in the Autodesk Simulation Mechanical (ASM) has been performed. The results of computer simulation are compared with the experimental results obtained earlier in a laboratory fire test performed on the structure having the same parameters, and subjected to identical heating regimen. The comparison of experimental and simulated displacement paths followed by the selected nodes of the considered structure with increasing temperature of its selected components constituted the basic criterion of numerical validation. The experimental and numerical estimates of critical temperature specified for the analyzed frame and associated with its fire resistance bearing capacity have been verified as well.

Keywords: steel frame, fire exposure, numerical modeling, computer simulation, validation

1. Introduction

The fire resistance evaluation for a steel frame bearing structure would be reliable only if the strong and multi sourced nonlinearities could be accounted for. The geometrical nonlinearity due to large displacements of structural components and joints subjected to direct fire exposure, and the material nonlinearity induced by the mechanical properties of structural steel in the fire temperature are especially important here. Due to these facts the computational procedure pertaining to the evaluation of fire resistance should be based on the appropriately generalized iterative incremental approach [1,2]. In the real design environment, the person performing the evaluation uses professional computer codes especially modified to execute this type of calculations. However, these codes differ in not only the way the structure and loads applied to it are modeled, but also the simplifications embedded in the code, formal assumptions and even the details of numerical algorithms used. Such differentiation results in more or less pronounced quantitative discrepancies in the results of calculations yielded by respective codes. In order to reliably judge, which numerical results describe the reality in the most precise manner one should perform the so called validation. A comparison of numerical results representing the solution of the same structural problem by two independent computer programs, namely SAFIR developed by *J.-M.Franssen* and his co workers at the University of Liege [4], and commercial Autodesk Simulation Mechanical, further denoted as ASM, constitutes the purpose of this paper. The critical temperature of the considered steel frame structure related to its ultimate fire bearing capacity is the basic criterion of evaluation adopted here. In the example analyzed here the limit state of this type will appear as the sudden increase in the horizontal displacements u of selected frame joints located at the level of horizontal beams.

2. Description of the experimental setup

The classical experiment performed in small scale by *Rubert* and *Schaumann* [5,6] has been selected as the basis for validation. This experiment dealt with a single story two aisle steel sway frame having the geometry, statical scheme and load distribution as depicted in Fig. 1. The beams and columns of this frame were constructed of IPE80 hot rolled I-beam made of St37 steel corresponding to the contemporary S235JRG2 steel, for which the experimentally determined 0,2% yield strength reached the value of $\sigma_y = 355$ MPa. During the experiment the heating simulating the fire was applied to the left aisle of the frame only, this means, that the right column and beam remained in ambient temperature during the whole simulated fire exposure. All the structural components of the frame were sufficiently braced in the direction perpendicular to the frame plane. The location of nodes in which the bracing of this type was added is denoted by the "x" mark in the Fig. 1.

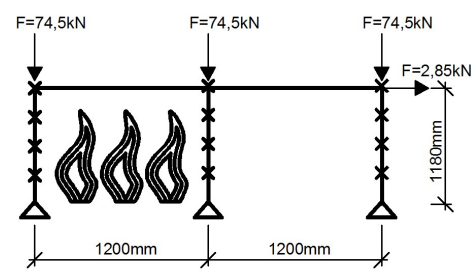


Figure 1: Statical scheme of the frame subjected to experiment.

3. Characteristics of the simulation models developed in SAFIR and ASM

The simulation of the experiment presented in chapter 2 has been performed in SAFIR using special 3 node bar elements (Fig. 2). Each bar element had 7 degrees of freedom in the end nodes (3 translational, 3 rotational and 1 additional to account for warping) and 1 degree of freedom in the middle node to account for nonlinear phenomena in axial deformation [3]. The evolution of steel properties when subjected to fire conditions has been assumed according to the EN1993-1-2 [7]. The torsional stiffness of the structure during the fire has not been reduced. An uneven distribution of steel temperature in the

cross sections of all bar elements has been taken into account, but this distribution has been assumed to remain constant along the length of each structural component modeled. The structure has been treated as subjected to dynamic loads to avoid potential instabilities during iterative calculations. The solution was found using *Newmark's* method.

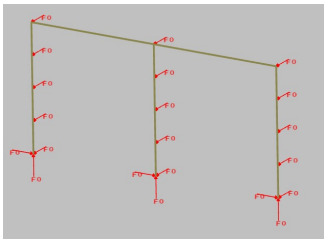
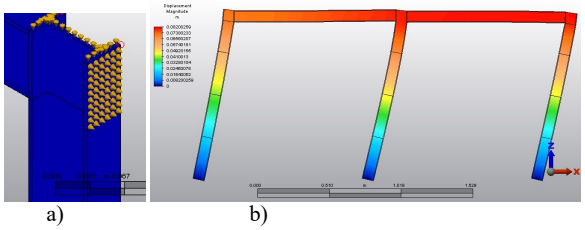


Figure 2: Bar model of the frame used in the SAFIR simulation.

Altogether 41491 tetrahedra, prism, wedge and brick 3D elements have been used to model the frame in ASM. All these elements had only vertex nodes. The vertical load has been applied as the evenly distributed surface traction to the tops of all columns, while the horizontal load has been applied as a surface traction to a rectangular area having the dimensions of 42x80 mm located at the top of right flange of the rightmost column. (Fig. 3a). The *Total Lagrangian* large displacement formulation has been used during the calculations with *Almansi* strain and *Cauchy* stress tensors. Because of the limitations in modeling the mechanical properties of steel, embedded in the code, the significant simplification of an elastic plastic material with isotropic hardening had to be used here to model the material behavior in the full range of temperatures covered.



a) b)

Figure 3: Frame model in the simulation performed by ASM:
a) application of vertical and horizontal loads,
b) in plane displacement magnitude.

4. Presentation of results

The experimentally determined horizontal displacements of the node „1" (at the top of the left column) and node „2" (at the top of the center column), denoted by u_1 and u_2 respectively, are depicted in Fig 4a) and 4b) as the functions of the steel temperature Θ (the dotted curves). These are accompanied by the graphs of displacements determined at the same points via the numerical simulations performed using SAFIR (continuous line marked safir) and ASM (continuous line marked ASM).

5. Concluding remarks

It seems that the results obtained by the authors confirm the usability of both codes to reliably estimate the fire resistance of steel frame structure. The much simpler in the application bar model, prepared in the environment of the SAFIR code, leads to the specification of the critical temperature for the considered frame at the distinctly lower level ($\Theta_{cr} \approx 510$°C) than the one obtained during experiment ($\Theta_{cr} \approx 540$°C) [2]. However, this result is located undoubtedly on the safe side. The simulation performed within the ASM computational environment yielded a result much closer to the experiment ($\Theta_{cr} \approx 550$°C), but as an overestimate it should be treated with caution in practical applications. However it is worth to note that both results are very close to the experiment, in spite of the simplifications in material model used in 3D modeling. Additionally, the numerical results seem to brace the experimental values, thus yielding an estimate from above and from below.

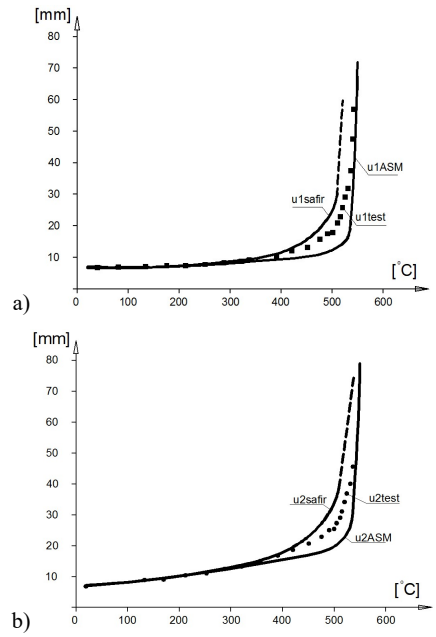


Figure 4: Displacement paths vs. temperature for the nodes:
a) at the top of left column (node „1"),
b) at the top of center column (node "2").

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