Assessing the structural safety of underground frame structures subjected to fire loading

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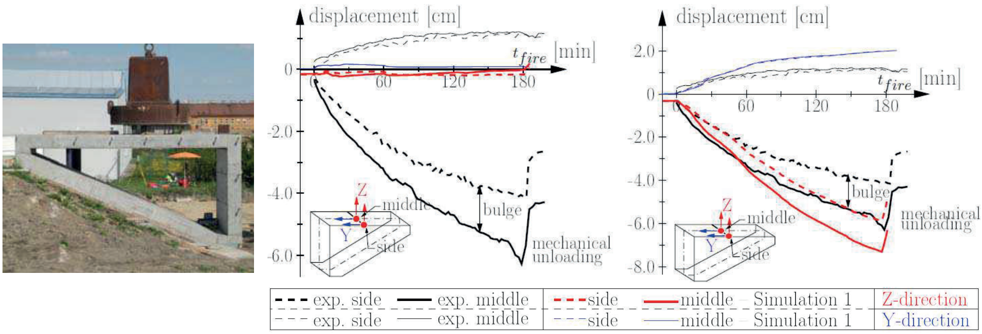
Summary

A nonlinear analysis tool to assess the structural safety of underground frame structures under fire loading is presented. The material and numerical model is validated by comparison of the numerical results with experimental data from large-scale fire experiments. Benchmark examples (real tunnel cross-sections) are analyzed, illustrating the advantages of the nonlinear over a linear-elastic analysis regarding an economic reinforcement design as well as the realistic prediction of the deformation behavior. Future work focuses on introduction of the realistic, nonlinear analysis tool in engineering practice as well as in design guidelines.

Keywords: concrete frame structures, fire loading, structural safety assessment, nonlinear analysis

The structural performance of underground frame structures subjected to fire loading can be investigated with numerical models of different levels of sophistication. The so-called equivalent temperature [1,3] is usually employed in engineering practice, simplifying the real non-linear temperature distribution in case of fire loading and transferring it into a linear temperature distribution over the cross-section. This approach allows the use of beam elements for numerical simulations which are easy to handle and widespread in present design programs considering linear-elastic material behavior. In order to perform more sophisticated and economic numerical simulations, more realistic analysis tools are required, taking the real non-linear material behavior and effects like spalling into account. The structural analysis tool developed within the Austrian research project "Safety of underground structures under fire loading" allows for consideration of these nonlinear effects on the material as well as the structural level (see [5,6] for details).



(a) (b) (c)

Fig. 1: Large-scale experiments for validation of the structural model:
(a) concrete frame (M 1:2, with mechanical loading) representing rectangular tunnel;
(b,c) comparison of experimental displacement results with numerically-obtained deformations using (b) a linear-elastic analysis according to [1] and (c) a nonlinear analysis according to [5,6] (see [5] for details)

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Before its application in engineering practice, the structural model has been validated by re-analysis of large-scale experiments on frame-like specimens (see Fig. 1(a) and [4,5] for details). Comparison of the numerical results from simulation approaches considering linear-elastic or nonlinear models (see [3,5] for details) highlighted the improved ability of the developed nonlinear analysis tool to realistically assess the safety of underground infrastructure under fire loading. The linear-elastic analysis (Fig. 1(a)) was not at all able to cover the experimentally-obtained deformations because – per definition – no plastic deformations caused by thermal loading can be considered in a linear-elastic analysis. On the other hand, the nonlinear analysis (Fig. 1(c)) gave results with satisfactory agreement with the experimental data. Even the bulge in longitudinal direction (i.e. the difference in displacement between symmetry plane and side face of the frame) caused by Eigenstrains in this direction was captured satisfactorily by the nonlinear analysis. This led to the conclusion that the consideration of nonlinear effects (such as plastic deformations) is crucial for obtaining realistic predictions of the structural behavior of fire-loaded structures.

After validation, the structural analysis tool has been implemented into commercial software packages. In this way, the developed nonlinear model is available to engineers for realistically predicting the structural performance of infrastructure under fire loading (e.g., consideration of stress and force redistribution, realistic prediction of the magnitude of deformations). In order to illustrate the improvements the nonlinear analysis tool brings in engineering practice, benchmark examples (i.e. real tunnel cross-sections with low overburden) were analyzed (see [3] for details). The analysis results illustrated the improved abilities of the nonlinear over the linear-elastic analysis regarding an economic design of the reinforcement layout and the prediction of realistic deformations: whereas additional reinforcement compared to the ultimate limit state (ULS) before fire was predicted in the top corner of the analyzed rectangular tunnel with the linear-elastic analysis, the reinforcement layout originating from the ULS was sufficient in case a nonlinear analysis was performed. This was attributed to the fact that the nonlinear analysis allows force redistributions from regions approaching the ULS (i.e., the top corner) to regions with a lower level of loading.

Currently, the results and conclusions of the performed structural analyses are incorporated in the design of an Austrian guideline [2], giving recommendations on the choice of the material and numerical model for analyzing underground structures under fire loading. Hereby, the choice of the optimal analysis tool (linear-elastic or nonlinear) is connected to the cross-sectional shape (circular, arched, rectangular etc.) as well as the duration of the fire and, hence, the required safety level (with the latter depending on the importance of the structure). The main goal of these recommendations is to assure an economic tunnel design under reasonable computational costs and a realistic prediction of the deformation behavior of underground structures under fire loading.

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