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Study on viscoplastic constitutive model of structural steel at elevated temperatures

(構造用鋼材の高温時の粘塑性構成則モデルに関する研究)

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主論文要旨

Elevated temperatures, such in the case of building fire, influence the material behavior. The material will suffer a loss of strength and stiffness with increasing temperatures and the linear elastic plastic stress-strain relationship of carbon steel at room temperature becomes non-linear. Thermal creep or stress relaxation occurs in the material, leading to strain rate-dependent and heating rate-dependent material properties.

The load-bearing capacity can be determined on four levels: the first level analyses the behavior of the material; on the second level, the material is considered as a two-dimensional shape (cross section) where the cross-sectional capacity is limited by local buckling for most of the common shapes of cross-sections in steel construction; the third level consists on the members, such as columns and beams, which load-bearing capacity can reach that of its corresponding cross-section, but member buckling occurs and reduces their capacity. Finally, the fourth level includes, for example, the members of the structure and analyses the behavior of the entire system. Each level is based and depends on the lower levels, but adds a new dimension to the problem.

The time-dependent response, creep of steel has a major role in predicting the collapse of steel columns subjected to elevated temperatures. Specially, creep leads to the creep buckling phenomenon, where the critical buckling load depends on slenderness, temperature and duration of exposure to high temperatures.

The success of simulating the collapsing behavior of steel columns under fire conditions depends on how accurately time-dependent mechanicals properties of
structural steels can be predicted at elevated temperatures and high stress levels. In the field of fire resistant design of steel buildings, high-temperature creep behavior is not often included in constitutive relationships, but has a significant influence on the fire response of the structures.

The aim of this study is to develop a multiplicative viscoplastic hardening model capable to generate approximate solutions within reasonable accuracy of the uniaxial monotonic behavior of steel material at elevated temperatures, creep behavior, and the identification of the material constants of the model.

To this end, the research question is: To what extent does the selected multiplicative viscoplastic hardening model reproduce the actual laboratory test of stub-columns and columns of steel material?

The research question is answered through combined experimental, analytical and computational studies. These studies are divided according to three kinds of steel material: SM490, BCR295 and STKR400. These are the most common grades of structural steel used in Japan, and for which very little elevated-temperature experimental data exist.

In the second chapter of this dissertation, the multiplicative viscoplastic hardening model was selected for time-dependent mechanical model of structural steel at elevated temperatures, and the material constants of the model were identified by using the stress-strain curves of tensile tests at two different strain rates at elevated temperatures.

All experimental results have been obtained using specimens of SM490 steel that were made on a previous study by Fujimoto, M., Furumura, T. and Abe, T. (literature 8). Uniaxial tensile test of SM490 under temperature (350°C, 400°C, 500°C, 550°C, 600°C, 700°C) and tensile speeds (1.0 and 0.05 mm/min), corresponding to the strain rates of about 1.5 %/minute (FAST tests) and 0.08%/ minute (SLOW tests) respectively, were carried out.

The experimental results showed that the flow stresses of SM490 were both temperature and strain rate dependent. Due to the rate dependency at high temperature, the ultimate stresses of FAST tests were higher than those of SLOW tests at 500°C ~700°C.

A multiplicative viscoplastic hardening model was selected to represent the uniaxial monotonic behavior of SM490 steel, and the set of material constants of the model was identified by the results of uniaxial tensile tests. The fitting parameters were determined with a nonlinear least squares optimization method through a Gauss-Newton iterative procedure. Comparing the material constants of strain-rate sensitivity in
literature 10 with those derived from the mechanical model in this study, the strain-rate sensitivity between them was almost the same.

By integrating the viscoplastic hardening model under constant stress condition, the Norton-Bailey creep law can be explicitly obtained. Therefore, the actual creep curves can be simulated by the creep model, which was derived from the viscoplastic hardening model, and it was possible to evaluate the validation of the mechanical model for estimation of actual creep response behavior. Correlations between measured and predicted creep strains for SM490 steel at elevated temperatures were obtained and a relatively good correspondence was found. Especially, the simulated creep curves at the highest applied stress level corresponded with the actual creep responses, and the predicted creep curves at low strain levels gave a little variation. This relation could depend on the fact that the stress response levels of the strain-hardening tests were higher than those of actual creep experiments.

In the third chapter, the obtained viscoplastic model was expanded into a multiaxial model and implemented into the general-purpose finite element program, ABAQUS, and the simulations of uniaxial creep tests and bending creep tests of SM490 structural steel specimens were carried out.

Thereby, the viscoplastic deformation behavior analysis was carried out to reproduce the tensile test in literature 14, the creep test in literature 8 and the bending creep test carried out in literature 15. Finite element method analyses of tensile and creep test of steel were carried out to confirm directly the accuracy of the numerical method by comparing its results with the laboratory tests under simple conditions results. Finite element analysis of bending creep test of steel analyzes the deformation behavior in the tensile and compression regions of the specimens due to a fixed bending moment load to demonstrate the validity of the material constitutive law and analytical method to reproduce the laboratory tests.

Comparison of the analytical values obtained by the finite element method using the viscoplastic model presented in literature 14 with the analytical values of the creep model based on the creep tests conducted in literature 8 to establish the validity and limitations when applying the viscoplastic model in literature 14 is detailed.

In the fourth chapter, the proposal of a material constitutive law of the high-temperature behavior model that can analyze and predict the deformation behavior of the cold-rolled rectangular steel tube columns in the loading heating test, and presents the identification of the material constants of the constitutive law from the experiment result is described in detail. Also, a method to accurately represent the stress-viscoplastic strain curve of cold-rolled rectangular steel box-column by using the
two original equations in the strain direction (the 2-n method) is presented. The proposed equation is applied to the stress-strain relationship, obtained from the compression test results of the cold-rolled rectangular steel pipe stub-column BCR295 to identify the material constants of the stress-viscoplastic strain curve at constant high temperature.

Finally, in the fifth chapter, analytical prediction of the deformation behavior during loading heating test of cold-rolled rectangular steel tube columns was carried out using the high-temperature elastic-plastic-creep analysis scheme of the finite element program ABAQUS described on the previous chapter. To verify the validity of the proposed constitutive law from this research, deformation behavior of stub-columns and columns made of rectangular steel tube STKR400 during high temperature loading test and load heating test are analyzed and comparison of test results and analysis values are presented.

It should be note that the method described on this dissertation can be similarly applied to steel material having a stress-strain relationship in which the strain rate is clearly indicated. In the future, it is expected that it will be used for prediction the deformation behavior of a structure made of various steel materials at the time of fire. However, some discrepancies arose in certain cases of the simulations, such in the uniaxial creep tests and bending creep tests, suggesting the necessity to develop a more appropriate mathematical form of the viscoplastic model.