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学位論文題目	**ANALYSIS OF CREEP BEHAVIOR OF HIGH STRENGTH STEEL COLUMNS AT ELEVATED TEMPERATURE** **（高強度鋼柱の高温時におけるクリープ挙動解析）**

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論文内容の要旨

This dissertation has reported results of the studies on the behavior of high strength steel columns when subjected to elevated temperatures due to fire. Analytical, computational, and experimental means were incorporated to conduct the research reported in this dissertation. The purpose of this research described in this dissertation is to gain a deeper understanding of the creep behavior of structural steel columns, particularly high strength steel, and to develop creep data and models for better analysis and design of steel structures subjected to fire. The investigation will include both analytical, computational, and experimental examinations of coupon tests and column tests at high temperatures. The study will focus on a number of series of high temperature coupon tests to ascertain the overall material properties, as well as a series of column tests at elevated temperatures. The steel material is not subjected to creep tests in this work, and the creep parameters are determined using general tensile tests at elevated temperatures. The experimental studies will focus on 3 types of high strength steel: YP400, YP500 and H-SA700, for which very little elevated temperature experimental data exists.

Chapter 2 of this dissertation is used to investigate the background of time- and temperature-dependent behavior of structural steel, referred to as thermal creep, and its relevance in forecasting the creep behavior of steel columns exposed to elevated temperatures caused by fire. The chapter began with discussing the definition of structural steel thermal creep. The effect of thermal creep on the stress-strain behavior of structural steel was then quantified using a variety of methods. Following the discussion of various methodologies for calculating the time- and temperature-dependent behavior of structural steel exposed to fire, a literature review was conducted. Important constitutive models for the thermal creep of structural steel at elevated temperatures were further reviewed. After reviewing the previous research and the background information provided on the phenomenon of time- and temperature-dependent stress-strain behavior of structural steel exposed to fire, the importance of creep deformations is proved and this implies that neglecting creep may result in very erroneous structural response estimates for structural steel, particularly for high strength steels. Moreover, there appears to be a lack of data on the creep behavior of high strength steels in general, and specifically YP400, YP500, and H-SA700 steels.

In chapter 3, efforts have been made to describe the phenomenon of time-dependent or creep buckling and its significance in predicting the buckling strength of steel columns subjected to elevated temperatures due to fire. The chapter was started by introducing the concept of creep buckling and establishing it as a time-dependent inelastic buckling phenomenon. Furthermore, a review of past studies was conducted to acquire a better understanding of the column behavior at elevated temperatures. Nevertheless, several additional potential factors impacting the subject to fire column's behavior are explored. As shown in the literature survey, the experimental data on columns at elevated temperatures are rather limited compared to column tests at normal temperature. Most of the column tests reported in the literature were accompanied by tension coupon tests conducted at room temperature. However, only a few past investigations included material characterization tests conducted at the same temperature as the column test. Nevertheless, the apparent importance of creep together with the limited number of studies related to the influence of creep on column buckling suggest the need for more quality research on elevated-temperature creep phenomenon. Specifically, the understanding of how to quantify creep effects on column buckling is still very limited and adequate experimental data is lacking

Chapter 4 began with an introduction to high strength steel and its mechanical properties. The results of tensile tests conducted at elevated temperatures on high yield point steels YP400 and YP500, as well as high strength steel H-SA700, were given, together with testing methodology and general properties. The process for developing the thermal creep model was also established based on Fields and Fields' creep material model and the actual creep behavior of the critical truss angle steel used in the WTC investigation. To identify the most correct creep parameters for the high strength steel utilized in this work, a trial-and-error approach was conducted to determine the most accurate stress-strain curves for the FE model that fit experimental data at various temperatures. The plastic material properties were then defined using hypothetical curves based on the observed stress-plastic strain relationship during experimental tests at various temperatures. Then, these thermal creep models were validated by comparing the stress-strain curves generated by Abaqus analytical results to those generated by experimental data. The experimental program and results described in this chapter generated essential experimental data on the influence of thermal creep on the elevated-temperature response of high strength steels, thereby filling significant gaps in the database of high strength steel mechanical properties at elevated temperatures. The test results provided in this chapter demonstrate that creep strains can be fairly severe in fire-prone building structures. This shows that disregarding creep may result in very erroneous structural response estimates for some types of structure-fire problems, such as steel columns exposed to fire. Additionally, when compared to experimental data, existing creep models for structural steel subjected to fire may provide inaccurate predictions.

Chapter 5 discussed various experimental results on high-strength steel columns, as well as some other research findings about potential influences on steel column behavior. The results of the computational method for column test based on material creep models provided in Chapter 4 are also analyzed using the Abaqus finite element software and compared to experimental results. Additionally, a thermal expansion coefficient is suggested for each steel grade YP400, YP500, and H-SA700, based on the vertical displacement of the column at temperatures less than 400 °C and on previously performed experiments. Additionally, two types of imperfection models (local and global buckling modes) are addressed in the study, including a different magnitude of imperfection. The outcomes of analyses with and without creep behavior were also compared. Plastic properties, thermal properties, and initial imperfection have all been investigated as potential influencers of time-dependent behaviors of high strength steels. The proposed method could be used with the same grade of steel without requiring full-scale structural or creep tests. In this study, the simulation analysis was used to determine the peak point of time and temperature versus displacement, deformation shape, and creep properties of the high yield point steel columns. The results were quite accurate when compared to the experimental results. The yield phenomenon may have an adverse effect on the analytical results. The experiment to determine the coefficient of thermal expansion is implied to be critical for simulating the behavior of steel structures, especially at temperatures below 400 °C. Furthermore, when conducting experiments over a wide temperature range, the absence of data should be avoided.

The final chapter ends with some observations and conclusions from this research. As shown in the literature survey, there is a scarcity of experimental data on thermal creep of structural steels, especially for high strength steels. Ignoring creep may lead to highly inaccurate predictions of structural response for some classes of structure-fire problems such as steel columns subjected to fire. The values of thermal expansion coefficient for high strength steel are identified and smaller than those indicated in standards. The approach of representing plastic properties as a logarithmic equation is well suitable for simulating thermal creep behavior using a finite element program. The approach for developing the creep model through general tensile tests was also demonstrated to be practical, owing to the high similarity between analytical and experimental data.

Several issues have been identified as requiring additional study or research as follows. The accuracy of the analytical solutions developed in this study needs to be improved due to discrepancies between analytical and experimental results at a variety of temperatures. It is necessary to evaluate the thermal creep of structural steel in compression. The creep models given in this study should be validated against various types of steel structures to ascertain their validity for high strength steels. Significant work is required to examine the internal forces that can have a dominating effect on column response. The time effects in the form of stress relaxation are of particular relevance because they may have an effect on the forces generated in steel columns due to restricted thermal expansion. The procedure for determining the creep parameters and creating the creep model needs to be simplified and made more precise.

論文審査の結果の要旨

本学位論文について，論文の構成および各章の内容を，火災科学，工学の見地から審査を行った.

建築構造物の代表的な構造形式の一つである鋼構造は，柱・梁を主要な構造形式としており，柱の荷重支持能力は建築物全体の構造安定性に非常に重要な役割をもつ．火災時を想定した高温時には，鋼材そのものの耐力低下，Young 係数の低下等が起こり，また部材端部の拘束条件により，熱膨張の影響も受ける．火災加熱の影響は数時間に及ぶこともあるが，普通鋼（降伏強さが 325 MPa 程度以下）では高温クリープの影響はほとんど現れないのに対して，高強度鋼では鋼材温度が 400℃を超えるとクリープの影響が明確になる．これまで定性的には知られていたものの，高強度鋼材による実大規模柱の耐火試験結果に基づく定量的検討は極めて少ない．本論文は，3 種類（YP400, YP500, H-SA700）の高強度鋼柱の実大規模耐火試験結果を高温クリープを考慮した有限要素解析手法で分析して，高温クリープがこの種の柱の耐火性能に及ぼす影響について定量的に論じたものである.

本論文は 6 章で構成されており，第 1 章では，研究の背景，目的および論文構成について述べている.

第 2 章では，鋼材の時間及び温度依存挙動である高温クリープの基本的な考え方を整理した上で，高温クリープに関する既往研究を詳細に調査し，Fields and Fields により提案されたべき乗則モデル，およびそれを改良した NIST モデルの有用性について論じている.

第 3 章では，クリープ挙動を含めた高温時鋼柱に関する既往の研究を詳細に調査し，柱の崩壊挙動に及ぼす要因として，材料の応力歪関係，高温クリープ特性，柱細長比，残留応力，線膨張係数等が過去に論じられているものの，とくに高温クリープに関しては定量的な研究が乏しく，これらについて検討する必要性を明確にしている.

第 4 章では，8 つのパラメータを持つべき乗則クリープモデル（Fields and Fields モデルを改良した NIST モデル）を採用し，YP400，YP500, H-SA700 の各鋼種の高温引張試験結果を適切に再現できるクリープパラメータを探索する手法を提案している．提案手法では，まず塑性領域の瞬時応力歪関係（時間依存挙動を含まない応力歪関係）を対数関数で表現し，これにクリープによる効果を組み入れている．このとき，クリープ効果の計算は, 前述の 8 パラメータべき乗則モデルを汎用有限要素解析コード ABAQUS の subroutine CREEP として組み込んで解析する．この手法で高温引張試験を再現解析し，パラメータの修正を行いながら多数回の試行錯誤によって，解析結果と高温引張試験結果が適合するパラメータの組み合わせを，YP400，YP500，H-SA700 の鋼種ごとに得ている.

第 5 章では，実大鋼柱（YP400，YP500 および H-SA700 鋼）の載荷加熱試験をクリ

ープの有無，初期不整の有無の異なる条件で有限要素解析により再現解析している．まず，高強度鋼の線膨張係数は Eurocode 3 等の設計規準で提案されている値よりも小さいことを，実大鋼柱の実験結果から線膨張係数を同定することで明らかにしている．形状初期不整については，全体座屈モード（1次固有モード）および局部座屈モード（1次固有モードと4次固有モードの重ね合わせ）による解析を実施して，実験結果に最も適合するのは，クリープを考慮し，局部座屈モードによる初期不整を考慮した解析であることを明示している．さらに，クリープを考慮しない解析は，実験結果を危険側（崩壊時間や崩壊温度が大きい側）に評価する傾向にあることを明確にしている．

第6章では，各章での結論を総括して本研究の成果を述べ，今後の課題について述べている．

本論文は高強度鋼材を対象とした高温引張試験結果を用いたクリープモデルパラメータの同定手法を提案し，さらに汎用有限要素コードを用いた解析手法を構築し，それを用いて高強度鋼柱のクリープを考慮した耐火性能を分析した研究として高く評価できるものであり，鋼構造耐火設計に大きな貢献があると考えられる．以上から，本論文は博士（工学）の学位論文として十分に価値あるものと認める．