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学 位 論 文 題 名

STATIC AND DYNAMIC BEHAVIOR OF BOLTED TIMBER JOINTS WITH STEEL SPLICE PLATES

(鋼添接板を有する木材ボルト接合部の静的および動的挙動に関する研究)

学位論文内容の要旨

It is well understood that the overall cyclic or dynamic responses of a wooden structure is a function of the performance of its connections. Ductile structures and structures containing ductile connections perform much better during seismic events that the timber structure having brittle joints. In timber structures, the earthquake energy is dissipated under several mechanisms such as internal friction, friction between structural and non-structural elements, and inelastic deformation of structural members (damages). However, large amount of this energy dissipation is mainly contributed through nonlinear load-deformation of their mechanical connections where the lateral loads are transmitted by bearing stress developed between the steel fasteners and the wood members. In areas that can anticipate very high earthquake intensities, an effort to increase the damping capacity of bolted timber joints will greatly reduce the amount of dissipated energy at other structural and non-structural members. This increase can be carried out by means of fastener pre-stressing. Extended yield model proposed in this study and test results of steel to timber joints under some different pre-stress levels show that bolt pre-tensioning largely increases the joint slip resistance at initial loading. Joint pre-stressing which is implemented by applying axial pre-tension force to the steel fasteners is expected to increase hysteretic damping capacity and cyclic properties of the joint, besides to increase the joint load-carrying capacity. These improved properties are required to be verified both experimentally and numerically by considering more reliable loading schemes: cyclic or dynamic loads.

Pre-stressed joints, which were obtained by applying 20 kN of axial pre-tension force to each steel fastener, and non-pre-stressed timber joints were tested under quasi-static cyclic loadings and via shaking table. Both joints were subjected to applied moment until failure. Pre-stress level on wood member of the pre-stressed joint was approximately equal to 1.6 MPa, which is about 90 percent of the allowable long-term edge-bearing stress of spruce species. In the cyclic test, effects of fastener pre-tensioning on hysteretic damping, cyclic stiffness, moment resistance and ductility of the joints were quantified. The seismic performances of both joints were examined through a series of shaking table test under some selected ground motions. A part form this shaking table test, a single-degree-of-freedom oscillator model was developed to numerically analyze the dynamic responses in which the joint stiffness was governed by a trilinear-skeleton hysteretic curve obtained from the cyclic test. Dynamic equilibrium equation of the model was solved by using step-by-step integration method with linear acceleration during time interval and constant viscous damping assumptions. Besides these cyclic and shaking table tests, stress relaxation measurement was conducted for about one year since the initial pre-stressing to evaluate the long-term effectiveness of this joint pre-stressing.

Hysteretic damping or the area enclosed by a hysteretic loop of the pre-stressed joints was several times greater than that of the non-pre-stressed joints. Hysteretic damping of the non-pre-stressed joints decreased as the number of cyclic load increased and its reduction occurred with a greater rate when the joints were cycled at higher rotation levels. On the other hand, the hysteretic damping of the pre-stressed joints during initial and final cycles was not much different. Eqtivalent viscous damping ratio of the non-pre-stressed joints decreased sharply as the cyclic rotation level increased and it was essentially caused by narrowing of the hysteretic loop at rotations close to zero points. While the equivalent viscous damping ratio of pre-stressed joints remained fairly constant for all cyclic rotation levels tested in this study. Frictional damping due to frictional action among the joint members greatly increased the equivalent viscous damping especially in the case of pre-stressed joints. Within a given rotation level, the continuously reversed cycles caused the stiffness to decrease from the initial cycle to the final cycle. Remaining inelastic slip component of irrecoverable embedment of wood beneath the steel fastenings during previous cycles was a potential reason toward this stiffness degradation, which was also manifested through the decrease of moment resistance. By increasing the number of cycles, moment resistance of the non-pre-stressed joint decreased exponentially and finally stabilized after four or five cycles. Moment resistance degradation of the pre-stressed joint however occurred almost linearly up to the final cycle with a lower degradation rate than that of the non-pre-stressed one.

Examination of dynamic properties of both joints in the shaking table tests confirmed the increase of frictional damping capacity and dynamic stiffness of the pre-stressed joints. Applying a pre-stress level of 1.6 MPa changed the viscous damping ratio of the joint from 6.59% to 9.40% and increased the dynamic stiffness of the joint by 112.5%. Frictional resistance among the joint components and increased friction between wood fibers, both of which are associated with transverse compression of the joint, contributed to the increase of vibration energy absorption. Under the ramped-acceleration motion, the moment-rotation relationship of the joint obtained form the shaking table test was almost similar to that attained by the cyclic test. Moment-rotation relation at the initial excitation indicated that less joint rotation was found in the pre-stressed joints than that in the non-pre-stressed joints for the same magnitude of moment resistance. Moreover, sudden increase of time-history responses caused by stiffness degradation of the joints was more substantial for the non-pre-stressed joints. When the applied moment exceeded the upper limit of interlayer slip, additional damping was potentially contributed since the experimental joint rotation did not grow rapidly. This additional damping was potentially due to pinching that isolated the mass of the oscillator model from high peak ground acceleration.

After being exposed to in-door environment condition for about one year since the initial pre-stressing, the average residual stress of the pre-stressed joints reaches a value of 0.23. This residual stress increases to 0.66 when the joints are re-stressed twice after three months and six months. Although large decrease of pre-tension force is found due to relaxation, the hysteretic damping of the joints without re-stressing is still relatively higher than that of the non-pre-stressed joints. Significant frictional damping contributed by the frictional resistance among the joint components is found to be proportional to the fastener residual stress. Based on the simulated stress relaxation curve, which is developed according to the four-element relaxation model, residual stress of the joints is negligible after five years if re-stressing is not applied. Without a regular re-stressing program therefore initial pre-stressing effect must not be considered in practice. However, about 20 percent of pre-stress level can be rationally expected when re-stressing is carried out annually. This small residual stress has significant effect on the cyclic performances of the joints; increasing the equivalent viscous damping from 0.08 (equivalent viscous damping the non-pre-stressed joints) to 0.18. In addition, this remaining pre-stress might be sufficient to keep the joint members close or in contact to each other so that the frictional damping caused by the secondary fastener axial force can effectively be facilitated at the early stage of joint deformation.

学位論文審査の要旨

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学位論文題名

STATIC AND DYNAMIC BEHAVIOR OF BOLTED TIMBER JOINTS WITH STEEL SPLICE PLATES

（鋼添接板を有する木材ボルト接合部の静的および動的挙動に関する研究）

わが国は、古来より木の文化を育んできており、日本の橋は木橋と位置付けられる。現存する木橋として、大月市の猿橋と岩国市の錦帯橋が国の重要文化財に指定されている。昭和30年頃よりモータリゼーションの発達にともない、橋梁材料は鉄筋コンクリートおよび鋼材が主流となり、木橋は公園内の小規模歩道橋に限られ、近代木橋の建設は極めて数少ない状況が続いていた。

最近に至って、木材の強度の面では集成材および鋼材との合成技術が進み、耐久性の面では防腐加工技術が進んできたため、また、自然環境保全工法の要望とも相俟って豊富な国内資源である木材を有効利用した木橋架設が再び見直されるようになり、その施工事例も増えている。しかし、木材接合部の静的特性および動的特性に関する研究は数少なく、近代木橋設計示方書の制定もなされていないのが現状である。

本論文は、鋼添接板を用いた木材ボルト接合部を対象として静的繰り返し曲げ載荷実験を行い、その履歴特性を明らかにし、また、振動台による動的載荷実験により固有振動特性を明らかにし、近代木橋性能設計に資する新たな知見を得たものである。

本論文は全7章から構成されており、各章の内容は以下のようである。

第1章では、研究の背景および既往の研究成果をまとめ、本研究の目的を明確に示し、各章の構成について記述している。

第2章では、鋼添接板を用いた2面せん断型木材ボルト接合部の静的耐力特性を検討している。木材ボルト接合部におけるせん断耐力の異方性は、釘や木ネジ接合に比較して大きいことを明らかにしている。ボルトの曲げ変形が小さいと、木材自身の強度曲げ変形が現れ、ボルトの曲げ変形が大きくなると異方性が緩和されることを提示している。複数のボルト配置を有する木材ボルト接合部が曲げモーメントを受ける場合、各ボルトに作用する力の方向を正確に把握することが重要であ

り、ボルトの中心間隔と縁端距離が不足すると耐力低下することを明らかにしている。また、曲げ耐力の算定式を提案し、実験値とも良好な一致を得ている。

第3章では、ボルトに導入される引張力とボルト自身の二次変形を考慮した終局耐力算定方法を提示している。有限変形問題を支配する仮想仕事方程式に基づき、有限要素法の手法により幾何学的非線形性と材料非線形性を考慮した接線剛性マトリックスの定式化に成功している。変位増分法により、良好な解を得ている。繊維方向および繊維直角方向とも木材ボルト接合部の荷重—変位曲線は実験結果と良い一致を得ている。木材のめり込み降伏とボルトの曲げ降伏を考えた従来の降伏理論を拡張した本終局耐力算定方法は有効であることを明らかにしている。

第4章では、静的繰り返し載荷実験および人力衝撃加振による自由振動実験により、木材ボルト接合部の履歴減衰について検討している。ボルトにプレストレスを導入した場合には、等価粘性減衰比がかなり増大することを確認している。また、木材ボルト接合部の初期剛性および基本固有振動数も増加することを明らかにしている。

第5章では、振動台を用いたスウィープ振動、正弦波および地震波入力加振のよる木材ボルト接合部の固有振動特性を調査している。ボルトにプレストレスを導入すると、鋼添接板と木材間の摩擦抵抗により剛性が増加し、基本固有振動数が増加することを明示している。また、安定的な履歴復元力特性が得られ、プレストレスを導入することの有効性が提示されている。

第6章では、ボルトに導入したプレストレスは、時間の経過とともに張力が減少するリラクゼーション (応力緩和) を確認している。ボルトに再度、プレストレスを導入することにより元の履歴復元力特性が得られことを明らかにし、摩擦減衰はほぼプレストレス量に比例することを記述している。このことより、数年経過後の木材ボルト接合部の剛性と減衰比を評価する算定式を提示している。

第7章では、各章で明らかとなった内容を要約し、本論文を総括している。

これを要するに、著者は鋼添接板を用いた木材ボルト接合部の複合非線形性を考慮した降伏理論を拡張的に発展し、プレストレスを導入した木材ボルト接合部の固有振動特性を明らかにし、耐震性能向上に資する新たな知見を得たものであり、橋梁工学、地震工学、木質構造学に貢献するところ大なるものがある。よって著者は、北海道大学博士 (工学) の学位を授与される資格あるものと認める。