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学位論文題目	Performance and Optimization of Large Deformable Elastic Braces for Seismic Resilient Structures (地震レジリエント構造のための大変形弾性ブレースの性能と最適化)
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## 論文内容の要旨

Seismic resilience of building structures has historically focused on preventing collapse during major earthquakes, with less emphasis on post-earthquake functionality and residual deformations. Conventional seismic control systems, such as base isolation, hysteretic dampers, and buckling-restrained braced frames, can provide efficient protection, but they usually cause large permanent deformations that make structures in a state of severe post-elastic deformation, which may reduce their serviceability and economy. A comprehensive study of Large Deformable Elastic Braces (LDEBs) is presented in this dissertation, which are proposed as an innovative structural technology for limiting residual deformations while maintaining elastic behaviors under extreme seismic loading conditions that would otherwise lead conventional members to yield.

Large Deformable Elastic Braces adopt a new concept of seismic design, as elastic restoring forces act throughout seismic action, and structures return to their original positions even when beams or columns have experienced plastic deformation. Unlike traditional hysteretic dampers, which require plastic behavior to dissipate energy, LDEBs provide an elastic response over their wide range of deformation, up to 1/70 of their original length, as confirmed in our previous research [1,2]. This outstanding deformation capability is enabled by precision-engineered geometric forms realized from high-strength steel sheets by laser cutting, which provide complex cross-sectional shapes that result in good stress distribution and thus avoid early yielding.

This study focuses on three basic knowledge gaps regarding LDEBs. First, although the theoretical basis and initial validation existed, a thorough experimental verification under extreme deformation levels exceeding 1/200 and 1/80 of the original length had not been systematically completed. The second issue was the buckle under compressive loading, one of the main failure modes for bracing

members and therefore required an intensive check to ensure they functioned reliably. Third, optimal stiffness distribution strategies for LDEBs in multi-degree-of-freedom structures were not investigated, which limited their application in structural engineering design practice.

The experimental test employed three optimized LDEBs specimens (F1-1, F1-2, and F2) fabricated from JIS G 3106 SM490A steel with yield strengths of 325 MPa, 408 MPa & 411 MPa, respectively. Tensile loading tests were performed to more than 100 mm on specimens with a length of 660 mm, equivalent to story drift ratios from about 1/13 to 1/6.5. In addition, parallel finite element analyses with material nonlinearity and combined material geometric nonlinearity present complete numerical techniques. The research developed close form predictive equations derived from classical beam theory that enable practical calculation of yielding deformation and force without requiring complex numerical simulations. These equations agreed well with the experimental tests and predicted yielding loads of 2.901 kN, 2.88 kN, and 6.120 kN for the three specimens, which were in close agreement with the experimental results.

The investigation of compressive behavior used an eigenvalue buckling analysis, an energy-principles approach, and experimental validation to show that LDEBs can be designed so that yielding consistently precedes elastic buckling. The energy-based method, which accounts for torsional strain energy, yielded conservative estimates ranging from 19.52 kN to 39.00 kN, depending on the test specimen and boundary conditions, and were generally above the yielding loads, which is 3.0 kN. Experimental tests validate the design concept, with no signs of buckling observed in all tested specimens up to the ultimate load of 5.90 kN. It was found that buckling capacity increased by 40–100% with improved end restraint conditions, with a significant effect on connection design in practice.

The development of the optimization framework was a considerable methodological improvement over combining particle swarm optimization algorithms with full Round Robin response surface methodology for two-degree-of-freedom structural systems. This combined approach effectively found global optimal LDEBs stiffness distributions and, at the same time, assessed solution reliability under various ground shaking conditions and boosted waves, using three different ground motion records with intensities of 50 kine velocity and 90 kine velocity. The optimal solutions showed that LDEBs systems provide maximum story drift mitigation of 15%–64% compared to unbraced frames, with performance most effective at moderate seismic intensities where life safety is significant. It was found that optimal stiffness distributions are highly sensitive to earthquake intensity, structural natural periods, and ground motions with different frequency contents, leading to valley shaped response surfaces in the solution space.

The practical implications of this research extend beyond academic contribution to immediate engineering applications. The methodology for validated predictive equations enables approximate predictive assessment without recourse to be advanced finite element analysis; the energy-based buckling evaluation yields conservative screening tools for connection design; and the optimization approach provides a systematic means of obtaining performance-based forms from both a design and a retrofit perspective. It provides additional benefits in high seismicity areas that require post-quake performance and rapid recovery, as LDEBs systems can restore the residual value of structures that would otherwise need costly repairs.

This work establishes LDEBs as a seismic protection technology that has reached maturity, with full scientific validation spanning field tests to system optimization. The research provides theoretical background, validated design tools, and optimization frames to support structural

engineers to confidently transfer LDEBs technology into performance based seismic design practice goals that contribute to the ultimate goal of making earthquake resilient infrastructure, not just to life safety but also damage recovery levels, where it may remain serviceable following major seismic incidents with retained functionality and economic worth, ready for serving communities in earthquake prone regions worldwide.

## 論文審査結果の要旨

建物は、人々を風雨や寒さ暑さなどから守るシェルターの役割がある一方で、大地震時などにおいて、場合によっては、建物被害や倒壊などで人々の安全や生命を脅かす要因になってしまうこともある。本論文は、大地震における建物の損傷を低減するための特殊部材の性能の調査や理論式の提案およびその有効な層方向剛性分布を最適化手法により調査したものである。

既往の研究では、建物の損傷を低減するための様々な制振装置が提案され、その有効性が、実験及び解析により検証されている。一方、申請者が取り上げる大変形弾性ブレースは、鋼板を特殊な形状に切断加工し、大弾性限を実現するものであり、この大弾性限の復元力により、大地震時の建物の残留変形や最大応答を低減する。この応答低減メカニズムは、従来の制振装置とは、大きく異なるものである。本論文での申請者の主な成果としては、この大変形弾性ブレースの引張荷重ならびに圧縮荷重下における挙動の有限要素解析、実験による検証にとどまらず、弾性限変形量と弾性限荷重の理論式まで導出し、その妥当性を確認していること（本論文第3章）、2層建物としての2自由度系における大変形弾性ブレースの効果的な剛性分布を最適化手法と地震応答解析により調査し、その傾向を明らかにしたこと（本論文第4章）である。この2点については、それぞれ、2編の査読付き学術雑誌に、その成果を公表済みである。

本審査は、2026年2月3日13:00より総合理工学部3号館209室で開催された。前回の予備審査での審査委員らによる指摘に対して、適切に対応されていること、英語による論文執筆と発表により十分な英語能力があること、論文の範囲内での質疑に対して適切に対応されていること、査読システムの確立されている国際オープンアクセス誌および国内雑誌に査読論文（関連論文）が2編（ともに筆頭）公表されていることを確認した。審査委員会は、本審査と同日の本審査後に開催され、審査委員による合議により、申請者は、博士（工学）の学位を授与するに適格と判断した。