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論文の内容の要旨

Beam-column joints play an important role in the seismic performance of RC moment-resisting frame structures since the collapse risk of RC moment frames can be considerably increased by joint failure. Thus, the integrity of beam-column joints is essential for structural integrity due to the transfer of loads effectively between beams and columns in moment frames during earthquakes. To ensure the joint integrity, the most modern seismic design codes such as ACI (USA), AIJ (Japan), EC8 (Europe), and NZS (New Zealand) have provisions for the seismic design of beam-column joints in RC moment frames based on extensive laboratory test results. These provisions were primarily based on the joint shear strength, independent of joint deformation. This could be related to the fact that numerous experimental and analytical studies focused on the basic shear strength of beam-column joints over the past few decades. The results of these studies revealed that beam-column joints with high shear stress levels (i.e., heavily reinforced beams) tend to fail in shear, regardless of the amount of shear reinforcement within the joint. Therefore, it was more logical to limit shear stresses within the joint by comparing the shear demand to a nominal shear capacity to prevent the joint from failure.

Despite this significant achievement, detailed investigations on the deformation of beam-column joints and their effects on the lateral response of moment frames have been relatively limited. This could be because the joint failure mechanism was studied separately from the failure mechanisms of the adjacent members in the majority of the existing studies. In fact, the separation of the failure mechanisms is difficult in many cases since the design parameters of both the members and the joint influence the failure mechanisms. Thus, to address these issues neglected in the first generation of the analytical and experimental studies on RC joints, experimental and analytical investigations were conducted to supplement and refine the existing knowledge as well as to develop a practical approach to evaluate the effect of joint deformation on the seismic response of RC moment-resisting frames.

The first part of this research focused on the identification of main parameters that significantly affect joint behavior. To this end, an analytical study was carried out using the quadruple flexural resistance (QFR) model. According to the results of the analytical research, the column-to-beam flexural strength ratio and joint shear reinforcement ratio were found to be important parameters apart from concrete strength and the amount of longitudinal reinforcement in the beam. They were selected as key test parameters. Moreover, the effect of joint shear reinforcement on joint behavior was found to be dependent on the quantity of beam longitudinal reinforcement and the flexural strength ratio.

A displacement-controlled cyclic loading test was conducted on eight half-scale interior joint specimens to investigate the combined effect of these two key parameters on the strength and deformation of RC interior beam-column joint connections.

The cyclic performance of each test specimen was examined in terms of the lateral resistance, failure modes, strain distributions of the beam, column, and joint reinforcements, joint shear stresses, and deformation components. Some of the important findings from the test are summarized below.

First, the test specimens with a larger flexural strength ratio of 1.5 exhibited better performance than those with a smaller strength ratio of 1.1, regardless of joint shear reinforcement ratio. Second, the increased amount of joint transverse reinforcement (steel percentage of 0.36% to 0.72%) gave less increase in the lateral strength and deformation capacity. Mainly, this phenomenon happened to the specimens with the largest amount of longitudinal reinforcement in the beam. These results were consistent with those of the analytical study. Third, all the test specimens exhibited joint failure. However, the failure was not caused by joint shear but joint moment because throughout the lateral loading, the shear stress induced in the joint increased even if the width of the diagonal shear cracks on the beam-column connection increased. Fourth, the degradation of the lateral load resulted from not the degradation of the joint shear stress but the loss of anchorage capacity of the beam longitudinal reinforcement passing through the joint.

Although the experimental study provided valuable information on the behavior of the interior beam-column joints, no clear correlation was found between the test variables and the deformation of the beam-column joints. The ultimate goal of this study was to develop a practical approach to evaluate the effect of joint deformation on the seismic response of RC moment-resisting frames. Therefore, a two-dimensional finite element investigation was carried out to examine the complex behavior of RC beam-column joints. The validation and calibration of the FE models were first done by simulating the test results. Subsequently, parametric investigations varying joint shear reinforcement ratio, strength ratio, joint aspect ratio, and area ratio of adjoining members were conducted on 39 full-scale FE models of the beam-column joint connection.

Some of the important findings from the finite element investigation are summarized below.

The results of the FE analysis were consistent with the observations made from the experiment. First, the beam-column joint connections with a larger flexural strength ratio of above 2 exhibited good performance and a relatively full hysteretic loop, although the joint shear reinforcement ratio is 0.3%. Joints remained elastic throughout the lateral loading, and the plastic hinges formed at beam ends. Second, the joint shear strength was increased by 5 to 10% with respect to an increase in the shear reinforcement ratio (0.3% to 0.7%), but the joint shear deformation was reduced approximately three times due to an increase in the joint shear reinforcement ratio. Third, the reduction of joint shear deformation was dependent upon the column-to-beam flexural strength ratio and area ratio of the members framing into the joint. For instance, the largest decrease in the joint shear deformation took place in the specimens with the larger values of the strength ratio and area ratio, and vice versa.

Based on the results of the experimental and analytical investigations, three simple equations were developed to predict the contribution of joint deformation to total deformation of interior beam-column joint connections corresponding to three different failures (i.e., joint failure before beam yielding, joint failure after beam yielding, and beam hinging failure). SDI values predicted by the equations reasonably agree with 50 test results of beam-column joints reported in the literature.

Finally, a nonlinear time history analysis was performed on three hypothetical RC perimeter frames in which interior joints were designed and detailed to exhibit three different failure modes, as mentioned above. The main purpose of this analysis was to ensure the reliability and effectiveness of the proposed approach in terms of multi-story RC moment resisting frames under seismic excitation. Some of the important findings from the seismic response analysis are summarized below.

First, the column-to-beam flexural strength ratio of 1.45 or less was found to be insufficient to protect columns from yielding. Also, the joint shear deformation was observed to increase with a decrease in the flexural strength ratio. Second, there was no noticeable difference in the lateral response of the considered three frames for the seismic excitation with PGA of 0.25*g* and 0.4*g* corresponding to the serviceability limit state because they behaved elastically. However, as the seismic intensity was increased further, aiming at the ultimate limit state, the difference in the interstory drift existed. Third, Exterior beam-column joints performed much better than interior joints since the shear deformation was significantly smaller than that of interior joints. This better performance was attributed to a larger column-to-beam flexural strength ratio and lower shear stress level in the joint. Fourth, the shear deformation index (SDI) of interior joints of the first and second stories in three frames was predicted by the proposed three equations. A reasonable agreement was found. Despite some disagreement between the predicted and observed SDI values, the proposed simple approach can consider additional interstory drifts due to joint shear deformation. Therefore, the equations are deemed useful and practical to identify inelastic joints in RC moment resisting frames without doing nonlinear static and dynamic analysis.

論文の審査結果の要旨

当学位論文審査委員会は、2021（令和3）年2月12日に論文発表会を開催し、論文内容の発表に続いて質疑応答と論文内容の審査を行った。審査結果を以下に要約する。

鉄筋コンクリート（RC）造建物に代表されるラーメン構造は、主に梁と柱を組み合わせて主構造が構成されている。梁柱接合部は部材間の力を伝達する重要な構造要素であり、特に構造物の地震時挙動および耐震性の点で非常に重要な役割を担っている。RC造に対する各国の耐震設計基準（日本、米国、欧州、豪州等）においては、数多くの既往の実験的あるいは解析的検討に基づき、接合部せん断強度に対する規定が定められている。既往の地震被害に基づき、梁や柱の鉄筋量が増大してきたが、これにより梁柱接合部は高いせん断応力が作用することが明らかにされてきたことから、各種設計基準では、地震時の接合部せん断応力レベルをせん断強度以下に抑えることが規定されてきた。

一方、梁柱接合部の変形は、構造物全体の変形に大きく寄与するにも関わらず、それに関する研究事例は接合部強度に関する研究に比べて圧倒的に少ない。これは、接合部の変形や損傷のメカニズムが、梁や柱およびそれらの接合部の様々な設計変数に大きく影響され、部材変形と接合部変形の分離が困難であったことにも起因している。そこで本研究では、実験的および解析的検討を通じて、梁柱接合部の変形と破壊の機構に関する既往の知見を補足および改善するとともに、RCラーメン構造全体の地震応答に及ぼす梁柱接合部の変形の影響を評価する実用的な手法を提案することを目的としたものである。地震によって損傷を受けた梁柱接合部の修復は困難であるため、新設構造物では強度ベースの設計により接合部損傷を抑制するのが一般的であるが、既設構造物においては接合部強度が必ずしも現行基準を満足していないため、本研究で提案する変形評価手法は、既設構造物の耐震診断において特に有用である。なお、梁柱接合部は、その形状に応じて十字型、ト型、T型、L型に分類されるが、本研究では十字型梁柱接合部を対象としている。

本学位論文の第1章および第2章では、以上のような本研究の背景と目的を述べるとともに、各国における梁柱接合部の現行耐震設計基準を調査・整理している。併せて、梁柱接合部の強度推定モデルに関する既往の研究を広く調査して知見を整理するとともに、日本の現行基準の元になっている接合部の曲げ抵抗理論に基づいた試計算の結果をまとめている。この試計算の結果に基づき、梁主筋量、柱梁の曲げ耐力比、接合部せん断補強筋量の三項目を主要な検討パラメータとして抽出している。

第3章では、前章で抽出した主要パラメータに基づき、合計8ケースの梁柱接合部試験体に対して静的正負交番載荷実験を実施した。ここでは各パラメータが接合部の破壊形態や強度に及ぼす影響について検討するとともに、詳細な変形計測に基づいて、全体変形に対する接合部変形の寄与率について検討した。その結果、接合部破壊が曲げ抵抗理論に基づいて説明されること、柱梁曲げ耐力比が大きい方が良好な耐震性を有すること、梁主筋量が大きくなると接合部せん断補強筋量による強度と変形の向上効果が薄れること、接合部の耐力低下がせん断抵抗力の低下でなく梁主筋の付着力低下に起因すること、全体変形に及ぼす接合部変形の寄与率が最大で30～50%程度に達すること等を実験的に明らかにした。

第4章および第5章では、梁柱接合部の強度と変形に及ぼす数多くの設計変数の影響を定量的に評価する

ことを目的として、二次元有限要素解析による解析的検討を行った。まず、第３章で実施した載荷実験を対象とした解析を実施し、使用する材料構成則と材料変数、境界条件等のモデル化方法を決定し、それを用いて 39 ケースの包括的な数値実験を実施した。その結果、柱梁曲げ耐力比が 2.0 以上であれば、接合部内せん断補強筋量が少なくても、強度・変形の観点で良好な性状が得られること、接合部せん断変形の抑制は、柱梁曲げ耐力比と断面積比の両方の影響を強く受けること等を解析的に明らかにした。

第６章では、第５章で実施した数値実験結果に基づき、全体変形に及ぼす梁柱接合部変形の影響度を定量的にかつ簡易的に算定する実用モデルの提案を試みた。梁、柱、接合部の形状寸法や鉄筋量等の設計変数に応じ、三種類の破壊形態（接合部破壊、梁降伏後の接合部破壊、梁曲げ破壊）を判定するパラメータを提案し、各破壊形態について、梁柱接合部の変形が全体変形に及ぼす寄与率を推定する簡易な式を提案した。さらに、接合部変形成分の実測結果が報告されている 50 ケースの接合部載荷試験結果を用いてこれらの提案式検証し、実用に供する推定精度を有していることを明らかにした。

第７章では、異なる配筋諸元を有する三種類の多層 RC ラーメン構造に対して二次元動的非線形有限要素解析を実施し、第６章で提案した簡易式の実地震時挙動に対する適用性について検討した。入力地震動は、1995 年の兵庫県南部地震において神戸海洋気象台で観測された実地震記録（南北成分）を、最大地動加速度 0.25g ～ 2.0g に振幅調整して用いた。その結果、提案式はいずれの構造においても一層および二層の梁柱接合部の変形を良好に推定し得ることが示され、本提案式により、接合部変形が全体変形に及ぼす付加的な変形成分を評価できることが明らかとなった。

第８章では、第７章までの結果をまとめて結びとしている。

以上のように、本研究では鉄筋コンクリートラーメン構造物の十字型梁柱接合部の強度のみならず変形を定量的に評価するとともに、それが全体変形に及ぼす影響を簡易に推定可能な実用的な式を提案しており、工学的に有意義な研究成果が得られたと言える。このことから、当学位論文審査委員会は、本論文が博士（学術）の学位にふさわしい内容であると判断した。

なお、本論文で得られた成果のうち、第３章の内容は査読付き国際会議（*The 6th International Conference on Construction Materials: Performance, Innovations, and Structural Implications*）に、第３章の一部ならびに第４章～第６章の内容は査読付き国際学術誌（*Buildings*）に、それぞれ論文が掲載されている。