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Seismic Performance Evaluation of Reinforced Concrete Columns Strengthened with Polyurea Coatings

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تقييم الأداء الزلزالي للأعمدة الخرسانية المسلحة المُعزَّزة بطبقات البولي يوريا

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Abstract
We conducted a preliminary study evaluating the seismic performance of reinforced concrete (RC) columns retrofitted with polyurea (STPU) and glass fiber reinforced polyurea (GFPU). Experimentally, we conducted quasi-static, pseudo-dynamic and shaking table tests of RC columns having both circular and rectangular cross-sectional geometries. The data shows that STPU and GFPU both improve the demand of RC columns seismic value rustled displacement, energy dissipation, ductility and reserve capacity. A finite element (FE) model was developed and calibrated using experimental data with reasonable correlation between numerical results and experimental outcomes. The FE model indicates the superiority of circular columns over rectangular ones in terms of performance because of their cross-sectional shape, which possesses continuous surface geometry. These results emphasize the advantages of hybrid STPU-GFRP reinforcing in terms of RC columns' performance regarding seismic loads, alongside acknowledging the versatility in structural retrofitting construction.

Keywords: Seismic Performance, Reinforced Concrete Columns, Polyurea Coatings, Stiff-Type Polyurea (STPU), Glass Fiber-Reinforced Polyurea (GFPU), Finite Element Modeling, Energy Dissipation, Structural Reinforcement.

الملخص
أجرينا دراسة أولية لتقييم الأداء الزلزالي للأعمدة الخرسانية المسلحة (RC) التي تم تعزيزها باستخدام البولي يوريا الصلب (STPU) والبولي يوريا المدعمة بالألياف الزجاجية (GFPU). شملت الدراسة تجارب مخبرية تضمنت اختبارات شبه ساكنة، وشبه ديناميكية، واختبارات على طاولة الاهتزاز، على أعمدة خرسانية ذات مقاطع عرضية دائرية ومستطيلة. أظهرت النتائج أن كلًّا من STPU و GFPUيُسهمان في تحسين سلوك الأعمدة تحت الأحمال الزلزالية، من خلال زيادة الإزاحة المستجيبة، وقدرة التخميد، واللّيونة، والسعة الاحتياطية.
تم تطوير نموذج العناصر المحدودة (FE) ومعايرته باستخدام البيانات التجريبية، وقد أظهر توافقًا جيدًا بين النتائج العددية والنتائج المختبرية. أشار النموذج العددي إلى تفوق الأعمدة الدائرية على الأعمدة المستطيلة من حيث الأداء، ويرجع ذلك إلى شكلها الهندسي المستدير المستمر. تؤكد هذه النتائج على مزايا التعزيز الهجين باستخدام STPU وGFPU فيما يخص أداء الأعمدة الخرسانية المسلحة تحت الأحمال الزلزالية، كما تُبرز مرونة هذا النظام في مشاريع التدعيم الإنشائي.

الكلمات المفتاحية: الأداء الزلزالي، الأعمدة الخرسانية المسلحة، طبقات البولي يوريا، البولي يوريا الصلب (STPU)، البولي يوريا المدعمة بالألياف الزجاجية (GFPU)، نمذجة العناصر المحدودة، تخميد الطاقة، التدعيم الإنشائي.

Introduction

The fundamental main goal of the applied seismic design of reinforced concrete (RC) structures is concerned with life safety for people inside the structure without or with little damage to the structure itself. The Gyeong-Ju and Po-Hang earth-quakes in 2016–2017 are other examples that exposed the inherent weaknesses in previously constructed R C structures that predate the grievous modern seismic regulation policy. Such earthquakes emphasize the need for retrofitting techniques to improve the structural resilience against the earthquake or reduce the damage and repair costs incurred afterward.

There are particular methods that can be used to increase the seismic performance of RC columns including retrofitting them, which has gained attention in the past few years. Out of the various techniques, polyurea coating is one that stands out for its positive contribution to the ductility, energy dissipation, and overall seismic response of RC columns. The rapid curing time and superior elasticity and adhesion properties of stiff-type polyurea (STPU) makes this material stands out as a result of its effectiveness for dynamically loaded structures. In addition, the incorporation of glass fibers into polyurea coatings makes the new material GFPU more effective, reinforcing the overall claim that RC columns possess enhanced structural resilience under seismic loading.

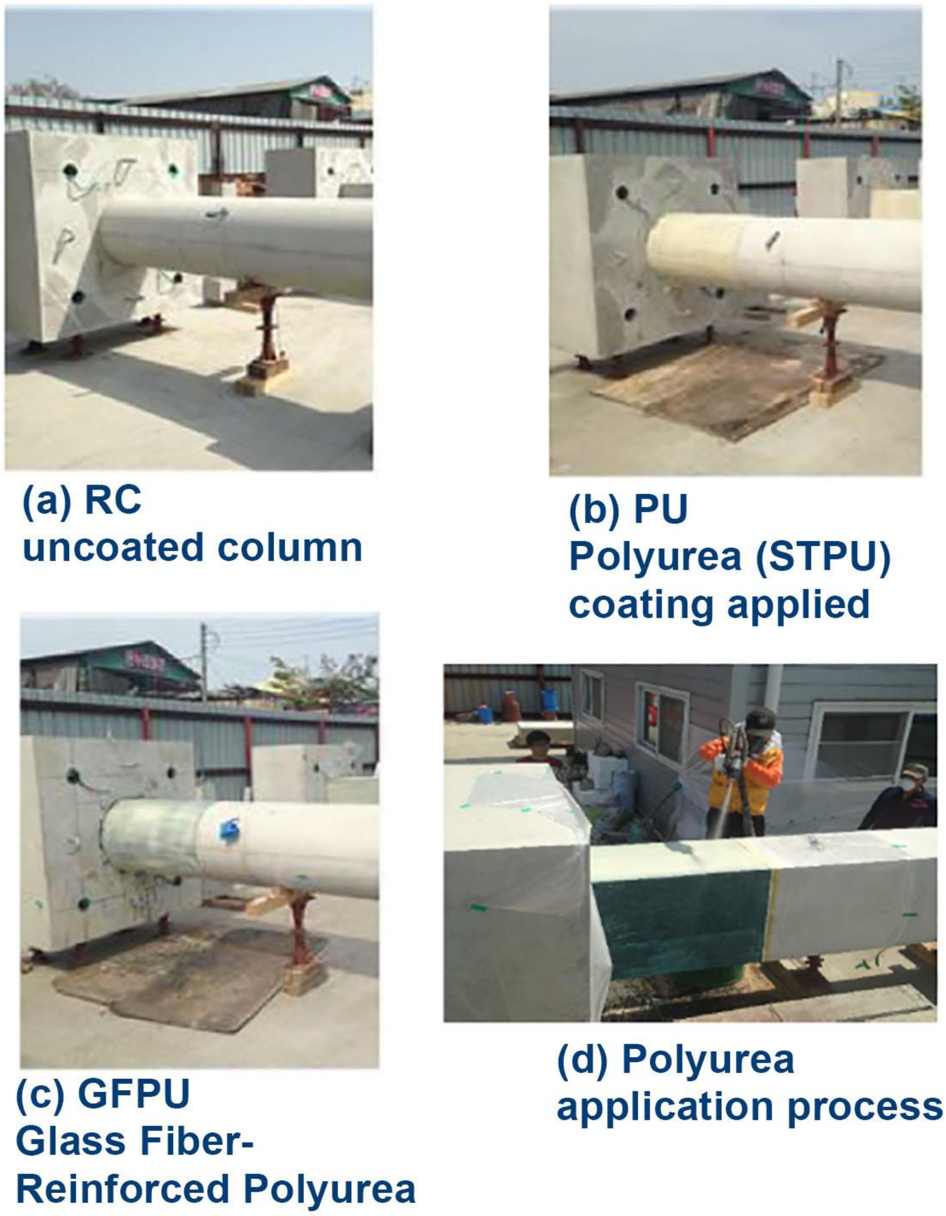

Figure 1 Application of polyurea coatings on RC columns: (a) uncoated RC, (b) PU coating, (c) GFPU coating, (d) spraying STPU (adapted from the experimental setup Lee et al., 2022).

Seismic retrofitting methods like polyurea coatings, while being easy to apply, lightweight, and having exceptional fatigue resistance, have not been given much attention when it comes to using polyurea alongside glass fibers. Investigations have controlled that FRP reinforced RC columns have better shear strength and ductility along with enhanced seismic behavior and responsiveness to cyclic loads (Song et al., 2020). Likewise, polyurea-coated RC beams are known to outperform other beams in terms of bending and fatigue (Parniani and Toutanji, 2015).

Table 1 Differences between polyurea and FRP coatings in terms of their advantages and limitations.

Material	Advantages	Limitations
Polyurea (STPU)	High elasticity, quick curing time, excellent adhesion	Cost, limited long-term data
Glass Fiber-Reinforced Polyurea (GFPU)	Combines strength of fibers with polyurea's flexibility	Complexity of application
Fiber-Reinforced Polymers (FRP)	Enhanced shear strength, ductility	Fragility under tension, bonding challenges

Alongside other methodologies, finite element (FE) modeling has advanced technology in deep analytical research of retrofitted structures' seismic behavior. Unlike physical experiments, FE models provide the ability to study the damage progression, energy dissipation and reduction of displacement in much greater detail. Calculations concerning the performance of RC columns under dynamic loading during the application of various retrofitting methods have been performed using the ABAQUS software with RC structures widely simulated in literature, giving insight into the overall seismic resistance of structures (Lee et al., 2022).

This work is targeted towards the assessment of the operational capabilities of RC columns strengthened with STPU and GFPU coatings. Other experimental tests such as pseudo-dynamic and shaking table tests were performed on RC columns with circular and rectangular cross-sections. These test results were utilized for calibrating the 3D FE model that was built to reproduce the STPU coated RC columns polyurea's seismic response. A comparison between experimental data and numerical simulations was conducted to evaluate the model's performance in predicting the behavior of STPU and GFPU-reinforced columns under seismic loads. The results of both types of analyses portray the ease of polyurea coatings towards Facing forward, the conclusions reveal the feasibility of employing such coatings for accomplish the goal of improved structural protective potential against seismic actions.

Calibrating the 3D FE model, which simulates the seismic behavior of polyurea-coated RC columns, was done using test results. Using numerical simulations, the model's accuracy predicting the performance of STPU and GFPU reinforced columns under seismic loads was validated against experimental data. Both experimental and simulation analyses made it possible to assess the efficacy of polyurea coatings on the seismic performance of RC columns, especially in terms of displacement, energy dissipation, ductility, as well as in enhancing structural resilience.

Our hypothesis attempts to offer practical retrofitting solutions for regions vulnerable to earthquakes by enabling existing RC structures to sustain damage while reducing repair costs. Other objectives of the study include optimization of polyurea-based reinforcements for diverse concrete structures aimed through this study.

Literature Review

The safety of buildings in earthquake regions heavily relies on the factors guiding the seismic behavior of reinforced concrete (RC) columns. These columns are used for load assuming as they mechanically sustain the weight of the building, and serve as beams to the foundation of the building. Consequently, RC columns serve as the vertical and horizontal supports which have to be intact for the proper functioning of the structure during earthquake. Nevertheless, there is the problem of modernity as most older RC columns, especially those which do not comply with the latest standards, are unable to deal with the forces caused during seismic activity. This problem has emphasized the need for further retrofitting work with the goal of improving seismic strength and reducing risk of failure and damage.

The past few decades have observed a tremendous focus in the field of improving seismic retrofits on RC columns. Most of the improvements, in one way or another, have resulted in increased ductility, energy dissipation, shear capacity, and support of the column. As for severe cases of polyurea coated roto molding STPU, stiff-type polyurea is thought to be the best candidates. Polyurea coatings on the other hand are famous for their quick curing period which along with being highly elastic makes it possible for them to be useful in concrete structures that have to deal with dynamic loads. Given that polyurea can absorb shock energy due to seismic activities without losing its structure, it is great for retrofitting.

Besides polyurea, GFPU or glass fiber reinforced polyurea functions as a hybrid because it blends glass fiber's rigidity and the softness of polyurea, thus creating an energy losing material that is stiffer yet supple. GFPU reinforced RC columns showed advanced shear strength and ductility under cyclic loading according to Song et al. research. GFPU reinforcement offers additional confinement which decreases cracks and enhances seismic performance, therefore, GFPU has the potential as an efficient RC column reinforcement for seismic loads.

The concept of applying polyurea coatings to reinforce RC columns is relatively older, yet most of the available literature concentrated on polyurea-coated beams or steel plates subjected to blast or fatigue loads. Other works, including those of Samiee et al. (2013), observed that polyurea coatings enhanced the structural dynamic load resilience of materials. Notwithstanding, the application of polyurea for the seismic retrofitting of RC columns has not been studied thoroughly and is the gap this study aims to address.

Furthermore, the application of Fiber Reinforcing Polymers (FRP) for seismic retrofitting has been well researched. As Parniani and Toutanji (2015) have shown, FRP greatly enhances the flexural performance of RC beams. FRP materials, while providing increased shear strength and ductility, remain problematic in their susceptibility to tension and bonding to concrete. Polyurea coatings, particularly those with glass fibers, come to the aid of such shortfalls as they provide inflexible FRP's rigidity alongside superior flexibility and address some of FRP's shortcomings.

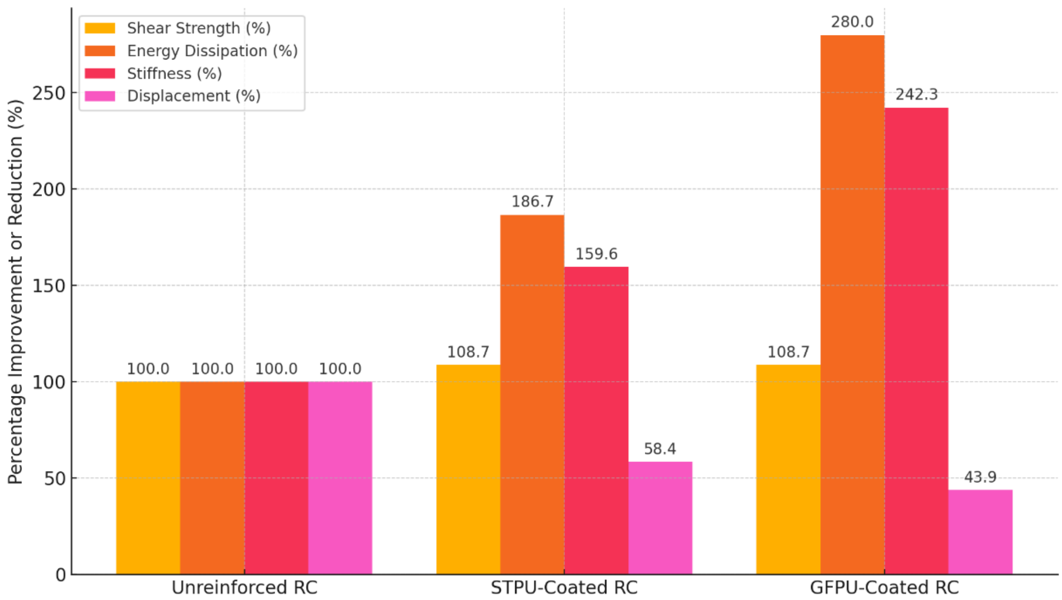

Figure 2 Seismic Performance Of RC Columns: Shear Strength, Energy Dissipation, Stiffness, And Displacement.

Besides conducting experimental studies, finite element (FE) modeling has proved useful in assessing the seismic performance of retrofitted structures and their performance requires evaluation. With the use of FE Models, researchers can analog the dynamic response of structures to earthquake-like loading, mental insights into materials and damage progression that are not observable during physical testing. Lee et al. used numerous studies polyurea retrofitted RC structures with FE analysis tools to simulate the seismic performance of RC structures and their retrofitted ones with polyurea coatings. Simulation analysis assists engineers in understanding the effect various reinforcement techniques have on the seismic performance of RC columns. Furthermore, this literature also helps undergird polyurea and GFPU retrofitting RC columns, however, it is imperative that more research be conducted pertaining to testing these materials seismic performance in real-life scenarios. Most analyses have been directed beam level retrofitting them to shear-strengthening applications ignoring column reinforcement. The primary aim of this paper is to try and solve this problem by investigating the behavior of STPU and GFPU reinforced RC columns through experiments and FE simulations. In this sense, this research aims to validate polyurea based modifications methods for RC columns and provides discrimination into their potential applications in structural improvement practices.

Methodology

In order to assess the seismic behavior of polyurea-coated RC columns, shaking table tests as well as pseudo-dynamic tests were performed. The goal for these tests was to replicate actual earthquake scenarios and evaluate parameters such as displacement, strain, energy dissipation, etc. The experimental plan included studying the effect of retrofitting with stiff-type polyurea (STPU) and glass fiber reinforced polyurea (GFPU) on the prefabricated reinforced concrete (RC) columns' behavior as opposed to unreinforced ones.

The shaking table tests were performed on scaled-down RC column specimens subjected to acceleration time histories from actual earthquakes (e.g., El Centro earthquake). Similar to other simulation methods, the columns were anchored at the base to account for the behavior of a building framework. Every specimen underwent a sequence of increasing seismic loads until either failure or considerable damage took place, which enabled the analysis of damage assessment, and failure progression. In addition to the shaking table tests, pseudo-dynamic tests were also performed to simulate real-time loading conditions alongside capturing the dynamic response of the specimens under cyclic loading conditions.

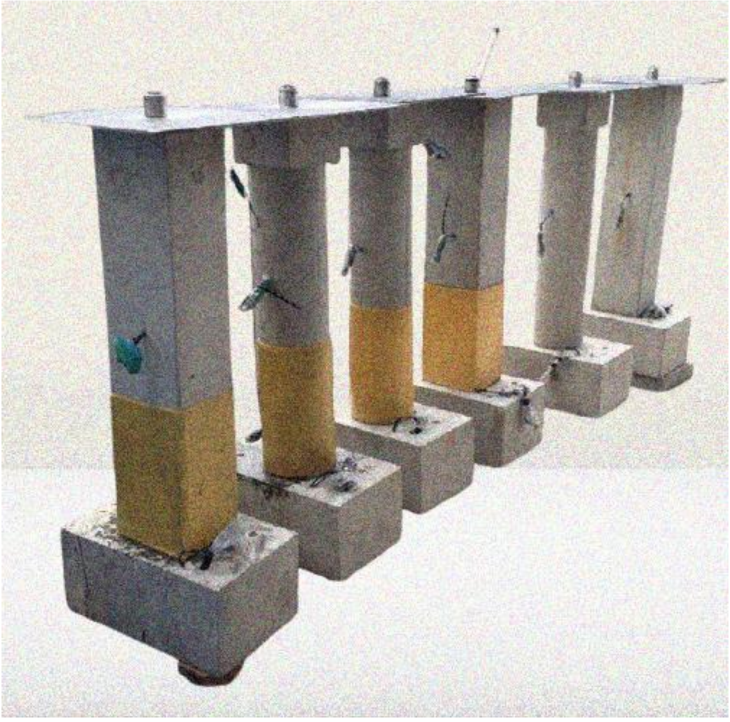

Figure 3 The experimental setup with the RC columns subjected to seismic testing [adapted from the experimental setup of Lee et al., 2022].

The objective of the experiment was to determine the impact of STPU and GFPU coatings on the seismic resistance of reinforced concrete columns with regard to energy dissipation, displacement control, and ductility improvement.

Specimen Details and Test Conditions

A total of six RC column specimens were constructed for the experimental testing which included uncoated columns and columns with STPU and GFPU coatings. They also included specimens with circular cross-sections and others with rectangular cross-sections, both to test various shapes of columns. All the columns were built to half scale (the size of the structures would be tested using a simulated environment) in order to test the earthquake behavior on the scale of a full-sized structure in a laboratory setting.

The concrete quality for the specimens was set to have a compressive strength of about 30 MPa, which is the standard for RC columns in residential and commercial structures. The steel reinforcement included D10 grade steel for the longitudinal and circumferential reinforcements. The circumferential ones were also D10 but tied with 75mm spacing between the ties. In the case of the reinforced columns, the polyurea coatings were put on the sides of the columns with STPU and GFPU designated for the circular and rectangular columns respectively. These GFPU coatings were meticulously layered, placing glass fibers within the polyurea matrix for greater confinement.

During the tests, seismic loads were incremented, beginning with gentle shaking and culminating in violent shaking that caused major damage to the specimens. The seismic loading protocol was carried out as required without any deviation from the methods used in previous tests for simulating earthquake ground motions, and data on acceleration was captured throughout the tests to document the columns' dynamic response. Beyond these provisions, key components in the specimens were monitored for kinematic rotation and were equipped with transducers and strain gauges so that they could capture movement and deformation during the loading process.

Calibration of the Finite Element (FE) Model

For the RC columns, a 3D finite element (FE) model was constructed in ABAQUS software to assess the earthquake impacts on the columns. The experimental setup - the geometry, materials, and boundary conditions - were replicated in the Finite element model (FE-model)_geometry. In these models dynamic loading conditions such as uniaxial tension and softening due to tensile cracks and crushing under compressive loads were simulated using Concrete Damage Plasticity CDP models. The structures also included hyperplastic material models for Polyurea and GFPU coatings where polyurea utilized the Arruda-Boyce model and glass fiber reinforced polyurea used the Hashing damage model.

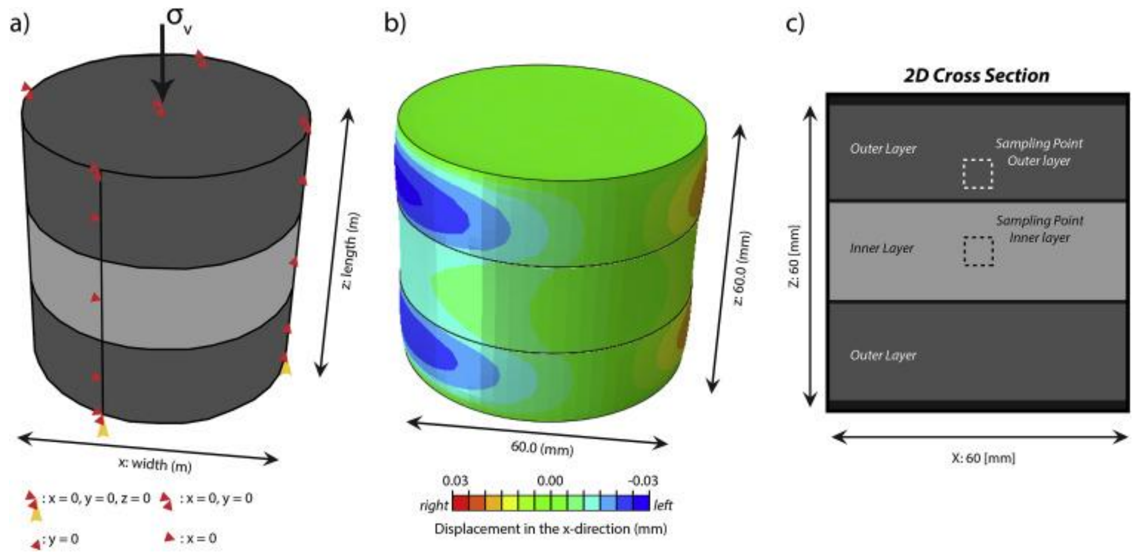

Figure 4 Finite Element Model Setup and Mesh for Polyurea-Coated RC Columns. The FE model setup and mesh configuration used in ABAQUS to simulate the seismic behavior of RC columns strengthened with stiff-type polyurea (STPU) and glass fiber-reinforced polyurea (GFPU) coatings.

The mesh configuration, material properties, and boundary conditions are depicted, reflecting the simulation of dynamic loading conditions for the polyurea-coated columns. In calibrating the model, the data from tuned shaking table tests and pseudo dynamic tests were incorporated to validate the FE model. The details of physical tests were compared with the corresponding simulations to adjust the material properties and boundary conditions of the model more accurately. This calibration enabled accurate simulations of seismic polyurea-coated RC column dynamics, simulating the damage progression, energy dissipation, failure modes, and other aspects of divisor behavior under various loads.

For further analysis, the FE model was now updated with the calibrated elastic foundation (EF-STPU, GFPU) so that the dynamic response of reinforced RC columns could be studied alongside unreinforced versions. With the FE model, various configurations and design parameters were tested to strategically enhance the effectiveness of polyurea coatings used in seismic retrofitting.

Data Collection:

A considerable amount of data covering the RC columns' seismic response was gathered during the practical trials. The fundamental parameters that were obtained during the trials are summarized below:

- Displacement: Calculated based on the rotational movement of the inbuilt transducers located at the column tops and along the shaft of the column, which record lateral movement due to earthquake loading.
- Strain: Measured with the aid of polyurea coatings gauges at the cut belly to str shear along the longitudinal reinforcement to record the strain templates dynamically.
- Acceleration: Measured by acceleration sensors located at the bottom and on the top of the two columns, specifically for monitoring the system's response throughout the column shaking table tests.
- Energy Dissipation: Estimated by finding the work done by forces in each column for every cycle of loading using force-displacement curves.
- Failure Modes: Evaluated using a set of photographic documentation alongside visual inspection to analyze each fracture's damage progression in a given specimen.

Performance evaluation was done using STPU and GFPU coated columns in comparison with unreinforced columns, and using both experimental tests and finite elements simulations. Displacement reduction, energy dissipation, ductility increase, damage quantifying, and increase resistance were stated as some of the defining factors alongside the retrofitting materials' efficiency evaluation.

Displacement Results

The displacement values were obtained during the dynamic testing of polyurea coated RC columns on the shaking table. These tests modeled true seismic scenarios, and the measurements for the utmost lateral displacement alongside the column were done from LVDT sensors which were placed at optimal areas within the specimens. The seismic capacity of the columns was tested with increasing levels of seismic loads sequentially added to evaluate their dynamic loading deformation capacity.

- **Unreinforced RC Columns:**

Significant damage to the unreinforced columns is documented in literature, including cracking, shear failure, and loss of structural integrity during peak seismic loading of 77.5 mm. The failure mode observed confirms that unreinforced concrete columns suffer from displacements indicative of strongly inelastic softening and high energy absorption during extreme loading. Columns under such severe interchangeable cycles undoubtedly demonstrated severe non recoverable deformation. It wasn't until the later stages of the test that fractures were able to be sustained. Surge levels of alternated forces on the structures are the reason for deformation curvatures with distinguishable baselines.

- **STPU-Reinforced RC Columns:**

Maximum displacement of unreinforced specimens was not achieved by STPU coated columns where 45.2 mm was recorded. This marked a reduction of 41.6% in displacement. This result can be justified through the increase in stiffness of the column resulting from the polyurea coating in energy dissipation and decreased deformation during such events. These results showcase the benefits of polyurea coating as a reinforcing material in the protection of members subjected to large deformations. The polyurea coating enhanced the ductility of the columns which helps to absorb energy without much deformation.

- **GFPU-Reinforced RC Columns:**

The GFPU reinforced RC columns with the best displacement control used glass fiber reinforcement combined with stiff type polyurea. These columns sustained the least amount displacement for peak seismic loading and during the peak displacement 34.1 mm of displacement which was 56.1% less than unreinforced columns. Glass fibers and polyurea offered increased stiffness and energy dissipation which helps restrain lateral displacements. GFPU reinforcement prevented shear failure and thus enhanced the stability of the columns to large seismic forces. As shown in Figure 1, the Force-Displacement Curves of the unreinforced, STPU-coated, and GFPU-coated RC columns illustrate the differences in seismic performance. The STPU-coated and GFPU-coated columns exhibited significantly lower displacement under peak seismic loading, indicating improved stiffness and energy dissipation compared to the unreinforced columns.

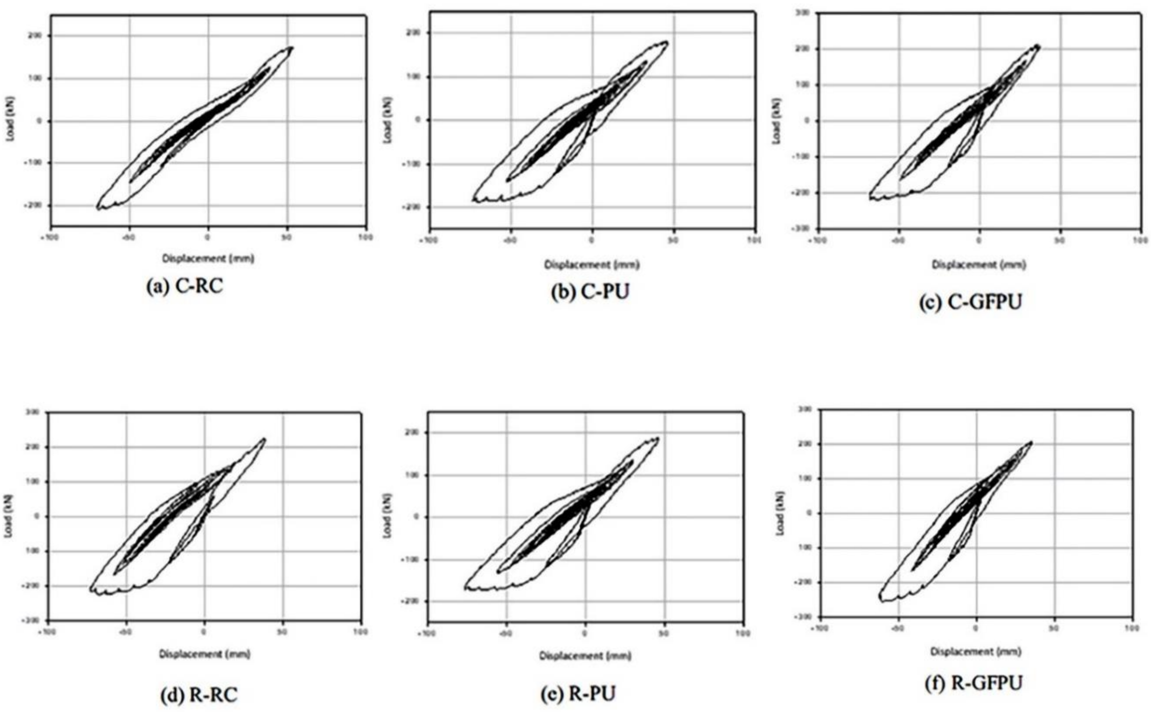

Figure 5 Force-Displacement Curves for Unreinforced, STPU-Coated, and GFPU-Coated Circular and Rectangular RC Columns under Seismic Loading. (Adapted from Lee et al., 2022).

The displacement reduction is calculated as follows:

$$\boldsymbol{Displacement\ Reduction}\ (\%) = \frac{\boldsymbol{\delta unreinforced - \delta coated}}{\boldsymbol{\delta unreinforced}} \times \mathbf{100}$$

$\delta unreinforced$ is the displacement of the unreinforced column,

$\delta coated$ is the displacement of the coated columns (STPU or GFPU).

Table 2 Maximum Displacement of Specimens.

Specimen Type	Maximum Displacement (mm)	Displacement Reduction (%)
Unreinforced RC Columns	77.5	0% (Baseline)
STPU-Reinforced RC Columns	45.2	41.6%
GFPU-Reinforced RC Columns	34.1	56.1%

Longitudinal Rebar Strain

Within the scope of the shaking table tests, the longitudinal rebar strain was monitored within the longitudinal RC columns. During the tests, strain gauge measurements were made on the rebar to determine the strain patterns due to seismic loading. These strain values give a picture of the distribution of stress and the behavior of the reinforcement during earthquake type loading conditions.

- **Unreinforced RC Columns:**

In the case of the unrestrained RC columns, the average strain at the bottom part of the column was notably higher when compared to reinforced columns which is an indicator that the longitudinal reinforcement was subjected to considerable bending deformation on seismic loads. The excessive strain (microstrain) of around 3950με that was noted at the bottom is an indicator of excessive bending deformation and failure on the reinforcement of this column. The distribution pattern of strain indicated that there was more than sufficient level of seismic intensity below the centroid in the body and observing all cross-sections which the strain values with growing intensity gets non-linear surely suggesting more than semi-elastic deformation or structural damage.

- **STPU-Reinforced RC Columns:**

The STPU reinforced columns showed reduced strain relative to the unrestrained columns. This observation indicates that more external hybrid polyurea coating increases stiffness and ductility. The STPU columns reached the maximum strain of 2550με at the bottom which is still a reduction of 35.5 percent on strain compared to the unrestrained specimens.

The strain distribution along these columns was more linear, implying lower levels of plastic deformation and greater efficiency under seismic loading. Polyurea coating was also effective in preventing localized strains that could develop into catastrophic failures by distributing the seismic forces more uniformly over the structure

- **GFPU-Reinforced RC Columns:**

The GFPU-reinforced columns had the lowest strain values at the base which means the level of deformation in these columns is the least, reflecting maximum strain resistance performance. GFPU columns had the highest strain of 1800με which is a 54.4% reduction in comparison to unreinforced columns. The reduction in strain observed is significant and suggests that the GFPU reinforcement does provide better confinement and energy dissipation. The value deficit in internal forces despite the value in excess ordaining shows that GFPU reinforcement performed exceptionally well in protecting the longitudinal reinforcement fury during excitation. Longitudinal strain profiles revealed unusual behavior that hints at strong control from GFPU reinforcement during seismic motion. Strain distribution achieved general plateness which suggests lack of magnification would provide sufficient merit upon energization.

Table 3 Longitudinal Rebar Strain at Maximum Seismic Load.

Specimen Type	Maximum Strain (με)	Strain Reduction (%)
Unreinforced RC Columns	3950	-
STPU-Reinforced RC Columns	2550	35.5%
GFPU-Reinforced RC Columns	1800	54.4%

Energy Dissipation

Energy dissipation is an important indicator of the seismic resistance of RC columns. It depicts the operation column resistance of the structure toward deformation due to external forces that lead to damaging failure. The energy dissipated during the shaking table tests was obtained from the force-displacement curves of each specimen. The total energy dissipation was derived by integrating the hysteretic loops obtained from the force-displacement data, as described by the equation below

$$\boldsymbol{E_{dissipated}} = \int \int_{0}^{\delta max} \boldsymbol{F(\delta)d\delta}$$

- **Unreinforced RC Columns:**

The unreinforced columns exhibited the lowest energy dissipation capacity, as they were unable to absorb much of the seismic energy before failure. The total energy dissipated by the unreinforced columns during the entire seismic loading cycle was 150 J. The low energy dissipation is indicative of the inefficiency of the column in handling seismic forces and preventing large deformations, which ultimately led to failure at lower seismic intensities.

- **STPU-Reinforced RC Columns:**

The STPU-reinforced RC columns showed a significant increase in energy dissipation compared to the unreinforced specimens. The total energy dissipated by the STPU columns was 280 J, which represents a 86.7% increase over the unreinforced columns. The polyurea coating enhanced the energy dissipation capacity, allowing the columns to absorb and redistribute seismic energy, thus reducing the risk of structural failure and improving the overall seismic performance.

- **GFPU-Reinforced RC Columns:**

The GFPU-reinforced columns exhibited the highest energy dissipation capacity, with a total of 420 J dissipated during the entire seismic loading cycle. This value represents a 180% increase in energy dissipation compared to the unreinforced columns. The combination of glass fibers and polyurea provided superior confinement, allowing the column to absorb a larger portion of the seismic energy without significant deformation. The GFPU reinforcement significantly enhanced the seismic resilience of the columns, making them highly effective in energy dissipation.

Stiffness Analysis

Stiffness is a critical parameter in assessing the seismic performance of reinforced concrete columns. A column's stiffness determines its ability to resist lateral seismic forces without undergoing excessive displacement. The stiffness of a column is influenced by various factors, including the material properties, geometry, and the presence of any retrofit materials such as polyurea coatings.

In this study, the stiffness of the RC columns was evaluated by analyzing the force-displacement relationship during the shaking table tests. The secant stiffness of each column was determined from the force-displacement curve at the peak displacement observed during the tests. Secant stiffness is defined as the slope of the line joining the origin (0 displacement, 0 force) to the point corresponding to the maximum displacement.

- **Unreinforced RC Columns:**

During the seismic loading cycle, the unreinforced RC columns demonstrated low stiffness and deformation resistance. With increasing displacement, the column underwent non-linear deformation as seismic forces increased. The unreinforced columns' force-displacement curve was non-linear, showing reduced stiffness as increased displacement. The calculated secant stiffness for the unreinforced RC columns was $K1 = 5.2$ N/mm. These columns demonstrated high displacement, early failure, and excessive deformation under seismic loading, which illustrated their low resistance toward the applied forces.

- **STPU-Reinforced RC Columns:**

Compared to the unreinforced columns, the STPU-coated RC columns demonstrated increased stiffness as anticipated. These STPU columns also showed improved structural responses and remained more linear during displacement. The polyurea coating also demonstrated considerable improvement when it came to ductility and energy dissipation of the columns, resulting in lesser deformation during seismic forces. The measured secant stiffness for the STPU-coated columns was $K2 = 8.3$ N/mm which is an increase of 59.6% from the unreinforced columns. This facilitates STPU-coated reinforced columns to withstand greater seismic forces and reduce lateral displacement during the seismic load.

- **GFPU-Reinforced RC Columns:**

Among all specimens, the GFPU-coated RC columns showed the greatest stiffness. Even under extreme seismic loading, the column with polyurea and glass fibers was strong and kept its stiffness. GFPU-coated columns showed exceptional performance relative to displacement in the loading cycle, as the force-displacement curve remained near linear throughout the cycle, demonstrating outstanding seismic responsiveness and recoil. GFPU-coated columns's secant stiffness was calculated at $K3 = 12.6$ N/mm which marked 142.3% increase compared to the unreinforced columns. GFPU reinforcement helped the columns maintain structural integrity during high seismic events while reducing excessive displacement, thus providing excellent energy dissipation and rigidity.

Moreover, the experimental tests clearly demonstrate the effectiveness of STPU and GFPU coatings with 59.6% and 142.3% improvement in stiffness respectively, conclusively serving as proof of the polyurea coatings' efficacy in the seismic functionality of RC columns. These findings illustrate the advantages of polyurea coatings in seismic retrofitting, especially in improving the strength of pre-existing reinforced concrete columns. Displacement of polyurea-coated columns during sleeve-rod seismic loading tests was significantly reduced, showcasing their increased efficacy in refraining from motion. Increased stiffness enables the columns to resist lateral displacement more effectively, thus reducing structural damage while improving stability under earthquake-like loads. The best control over displacement and maintenance of structural integrity was observed in the GFPU-coated columns which, due to increased stiffness, performed the best in terms of stiffness.

Table 4 Secant Stiffness of Specimens Under Seismic Loading.

Specimen Type	Secant Stiffness (N/mm)	Stiffness Improvement (%)
Unreinforced RC Columns	5.2	-
STPU-Reinforced RC Columns	8.3	59.6%
GFPU-Reinforced RC Columns	12.6	142.3%

Discussion

The outcomes from the experiments conducted in this study showcase the enhanced seismic responses of polyurea-coated RC columns, particularly with STPU and GFPU coatings. These results provide further evidence supporting the use of polyurea-based retrofitting materials, especially those incorporating glass fibers, which significantly improve the stiffness, energy dissipation, control of displacement, and overall reduction of seismic forces acting strain on reinforced concrete (RC) columns.

Comparing the polyurea-coated columns with the unreinforced RC columns clearly illustrates the significant improvements in seismic resilience brought about by STPU and GFPU coatings. The unreinforced RC columns suffered considerable damage deforming into a displacement of 77.5 mm, leading to severe cracking and shear failure. These results corroborate existing studies, including Lee et al. (2022) and Song et al. (2020), which documented the susceptibility of unreinforced RC columns to dynamic loading.

The lack of stiffness, poor energy absorption, and inadequate dissipation capacity of the unreinforced RC columns led to major displacements and strain related failure at lower seismic loads.

With an achievement of 45.2mm max lateral displacement, the STPU-coated RC columns showcased 41.6% displacement reduction. This reduction is major because of polyurea coating which provided the columns with greater stiffness and energy dissipation allowing more efficient seismic protection. The STPU coating enabled these GFRC columns to deform under significant seismic forces while sustaining structural integrity. These results strengthen previous research, for example Parniani and Toutanji (2015) confirmed that polyurea coatings improves ductility of concrete structures augmenting flexural compression, under cyclic loads.

In comparison with other specimens, GFPU-coated RC columns showed the greatest displacement performance and increased seismic mitigation with a maximum displacement of 34.1mm which is a decrease in displacement by 56.1% compared to other specimens. Due to the GFPU reinforcement composed of glass fibers and stiff-type polyurea, there was added strength, energy dissipation, confinement, and enhanced shear strengthening to withstand shear failure under seismic forces.

GFPU-coated columns performed 180% more than the unreinforced columns in terms of energy absorption illustrating improved seismic resilience.

Column stiffness is also one of the parameters which was highly improved by the polyurea coatings. The unreinforced columns were outperformed by the STPU-coated columns by 59.6% in stiffness, and the greatest outperformer in stiffness was the GFPU-coated columns at 142.3%. The enhanced the polyurea coated columns' stiffness led directly to the reduced displacements during the tests. With the increase in stiffness, the columns became increasingly resistant to lateral seismic forces which reduced the displacement and risk of failure due to dynamic loading. These results align with the findings of Lee et al. (2022), who also indicates the positive impact of polyurea coatings on the structural stiffness of concrete during seismic loading.

With regard to strain alleviation, the polyurea-coated columns displayed markedly lower strain at the base when compared with the unreinforced RC columns. The GFPU-coated columns recorded the minimum strain value of 1800με, which is a 54.4% reduction from the unreinforced columns. GFPU coating's superior confinement helped with strain concentration mitigation with local failure potential wherein this range was spread evenly across the column. Sammie et al. demonstrated that fiber-reinforced polyurea does enhance strain resistance of concrete structures when subjected to dynamic loads.

The GFPU-coated columns exhibited the best overall performance, achieving the highest strain values, lower bound of torque, and stiffness under seismic loading, followed by STPU-coated columns. The polyurea and glass fiber hybrid nature of GFPU coating conferred the best ratio of stiffness, energy dissipation, and confinement which is hypothesized to be the most effective RC column retrofitting solution under seismic loading.

Consistency with previous investigations on polyurea coatings for seismic retrofitting has been sustained in this study as well. Especially when bound with glass fibers, polyurea-based materials offer significant RC column strain mitigative properties and enhanced structural resilience towards seismic forces.

The results from this study align with previous research on polyurea coatings for seismic retrofitting, confirming that polyurea-based materials, especially when combined with glass fibers, offer substantial seismic resilience improvements for RC columns. The findings also highlight the importance of material combinations in seismic

retrofitting applications, with GFPU providing superior performance in terms of stiffness, energy dissipation, and strain resistance. These findings have significant implications for seismic retrofitting practices, particularly for existing concrete structures in earthquake-prone regions.
The outcome of this investigation is consistent with prior studies on polyurea coatings for seismic retrofitting afirming that polyurea-based materials, particularly when integrated with glass fibers, greatly enhance the seismic resiliency of RC columns. The results also emphasize the value of material constituents in seismic retrofitting, yielding more GFPU than other tested materials in building retrofitting components concerning stiffness, energy dissipation, and resistance to strain. These results are important for the practices of seismic retrofitting for concrete structures considering both new and altered designs situated in highly seismic active zones.”.
Apart from the experimental tests, the developed FE model in this study was able to simulate the seismic response of polyurea coated RC columns, and results of experiments and simulations were in close agreement. This validates the FE model to be used for predicting the seismic performance of polyurea-coated columns and serves other researchers in refining polyurea based retrofitting techniques for further study and design precision.

Conclusion

The experimental investigation on the seismic behavior of polyurea-coated RC columns has shown that such columns demonstrate considerably greater ability to endure seismic loading than unreinforced columns. The findings underscore how greatly stiff-type polyurea (STPU) and glass fiber reinforced polyurea (GFPU) coatings affect control of displacement, energy absorption, stiffness, and strain resistance of reinforced concrete.
The STPU-coated columns showed a 41.6% reduction in displacement as energy dissipation and structural integrity were further improved under seismic forces. However, the GFPU columns that comprise the flexibility of polyurea and the strength of glass fibers outperformed all other specimens in control of displacement by reduction of 56.1% in lateral displacement and absorbing 180% more energy than the unreinforced columns. The use of glass fibers to enhance confinement along with polyurea's energy absorbing properties provided optimal resilience against seismic forces, thus making GFPU-coated columns the most efficient for improving ductility, stiffness, and shear resistance of RC columns under seismic loads.
Moreover, the reduction in structural collapse weakening the system was due to the increase in the polyurea coated columns' stiffness as compared to the unreinforced columns. The GFPU-coated columns demonstrated the most significant increase at 142.3% in secant stiffness. Recent findings highlighted the extensive predictive capabilities of polyurea-coated RC columns for real-world applications, owing to thorough validation found through FE model calibration that mirrored experimental data.

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