Investigating the Potential Applications of Elastomeric Polymers (Such As Polyuria And Polyurethane) For Accelerated Bridge Construction And Retrofit

Quarterly Progress Report
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Project Abstract

Elastomeric polymers such as polyurea and polyurethane are nonlinear elastic materials with high tensile strength and strain capacity, adhesiveness, and resistance to permeability and environmental conditions. They have been used commercially as waterproofing and anti-blast coating for reinforced concrete components. While the elastomeric polymer is an interesting material with unique characteristics, there has been limited research on its potential structural applications. A number of research studies have shown the remarkable increase in flexural and shear strength of polyurea coated reinforced concrete beams. Further research is needed to explore the application of the polyurea coating system as a new structural material in the bridge industry.

This proposal takes the first step of a long-term research vision to examine and investigate the innovative applications of elastomeric polymers and specifically polyurea coating in accelerated bridge construction. Our focus is on the application of elastomeric polymer coatings for the design and retrofit of bridge girders. There are three aspects that can be considered for this application: *(i)* enhancing the flexural and shear strength of the beam through the application of a spray coating, *(ii)* enhancing the weather resistivity, which is especially important for side beams, and most importantly, *(iii)* over height vehicle collision impact resistance. This proposal only focuses on the flexural and shear strength of polyurea coated RC beams. This simple step is taken to start gaining experience and knowledge on this relatively new material, and incrementally examine other aspects of the applications and other potential applications through future proposals and other funding opportunities. We plan for an experimental-analytical research effort, to develop simple phenomenological material models for the polyurea coating system and to investigate the potential cost vs. benefit of the coating in the design and retrofit of side girders.

Research Plan

1. Statement of Problem

Based on the collective studies in the literature, it can be concluded that polyurea coating system (Figure 1):

- Increases the flexural and shear strength of RC beams and slabs. It also increases the ductility and failure deformation of RC beams and slabs (which adds to the structural safety by providing alarming deformations before failure) (e.g., [1]–[3]),
- Provides waterproofing and environmental resistance to RC surfaces, and has good resistance to deteriorating environmental conditions (e.g., freeze-thaw and deicing agents),
- Provides a remarkable local energy dissipation capacity, due to the deformation-induced glass transition of the material, which can enhance the impact resistance of members,
- Is easy to apply (spray coating), dries fast, and has a good bond with the concrete surface, which makes it a solution for on-the-ground as well as in-situ construction and retrofit applications.

Based on the outlined conclusions from the literature, the polyurea coating system is an interesting material with remarkable characteristics that can help to improve the multi-hazard design, construction, and retrofit of accelerated bridge components, with minimum impact on the construction time and site. Figure 2 summarizes the potential applications of the polyurea system in accelerated bridge construction. Despite the significant body of related literature, the practical development of design and construction guidelines requires further experimental and analytical research. This is considering the relatively new introduction of polyurea systems in the structural application and especially the bridge industry.

(a) (b) (c)

Figure 1: Application of polyurea coating (a) masonry slab (photo is taken from [4]*), (b) RC beam specimens (photo is taken from* [3]*), and (c) concrete pipe (photo is taken from* [5]*).*

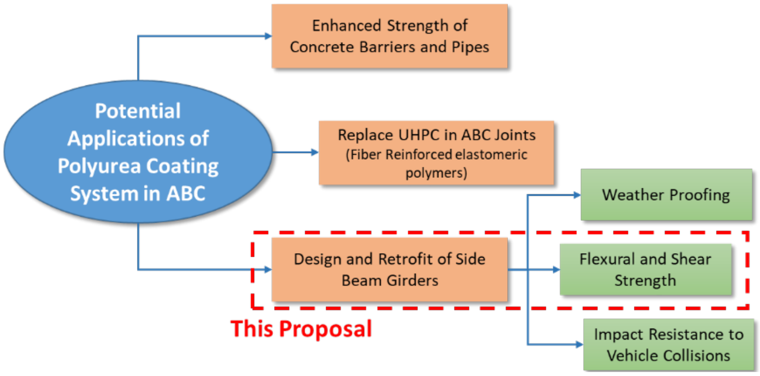

Figure 2: Potential applications of the polyurea system in accelerated bridge construction. This proposal takes the first step of a long-term research vision to examine and investigate the innovative application of the polyurea coating system.

2. Research Approach and Plan

This proposal takes the first step of a long-term research vision to examine and investigate the innovative applications of elastomeric polymers and specifically polyurea coating in accelerated bridge construction. The focus of this proposal is on the application of elastomeric polymer coatings for the design and retrofit of side beams in RC girder bridges. There are three aspects that can be considered for this application: enhancing the flexural and shear strength of the beam through the application of a spray coating, enhancing the weather resistivity – which is especially important for side beams – and, most importantly, overheight vehicle collision impact resistance. This proposal only focuses on the flexural and shear strength of polyurea coated RC beams. This simple step is taken to start gaining experience and knowledge on this relatively new material, and incrementally examine other aspects of the applications and other potential applications through a future proposal and other funding opportunities (see Figure 2). The research proposal included 4 tasks as summarized below.

Task 1 – Literature Review

A comprehensive literature review will be performed on the polyurea material and coating system for structural application, including the experimental results, numerical modeling, material models, etc.

Task 2 – Coupon Sample Tests

A series of polyurea coupon samples will be tested under uniaxial cyclic loading scenarios to develop a phenomenological stress-strain and viscosity material model.

Task 3 – Material Model Implementation and FE Numerical Studies
The phenomenological material model will be implemented in a FE simulation platform (e.g., LS DYNA) and will be used to model the response behavior of coated RC beam specimens tested in the literature. The analysis results will be compared with the experimental counterparts provided in the literature to validate the modeling techniques. A model calibration method based on Bayesian inference will be utilized for model calibration and reducing the discrepancies between simulation and experimental results.

Task 4 – Parametric Studies & Economic Analysis
With the calibrated FE model and modeling techniques developed in Task 3, a parametric study will be performed to examine the increase in flexural and shear strength capacity of bridge girder beams due to the polyurea coating. The cost of the polyurea system vs. the increase in strength will be compared with similar solutions (e.g., FRP) to provide an estimate of the economic feasibility of the new material. This step will pave the way to investigate the other potential benefits of polyurea systems for side girder design and retrofit.

The project was planned to be completed in 12 months starting from August 2020 (Table 1).

Table 1: Proposed project timeline.

Year	2021											
Month	1	2	3	4	5	6	7	8	9	10	11	12
Task												
Task 1: Literature Review	🟧	🟧	🟧									
Task 2: Coupon Sample Tests			🟧	🟧								
Task 3: FE Studies					🟧	🟧	🟧	🟧				
Task 4: Parametric Studies									🟧	🟧	🟧	🟧

Progress Report

COVID19-related delays: Due to the Covid-19 pandemic and the closure of U.S. embassies, we could not admit the targeted student researcher that was supposed to join us from the fall semester of 2020 and work on the project. Therefore, the project progress has been delayed for about 5 months (August-December).

We were able to identify and hire a master's student, Pawan Acharya, who has joined our program since January 2021. The updated project timeline would be as follows.

Task 1 – Literature Review: January 2021 – March 2021 (100% completed)

Task 2 – Coupon Sample Tests: March 2021 – April 2021 (in starting phase)

Task 3 – FE Studies: May 2021 – August 2021

Task 4 – Parametric Studies: September 2021 – December 2021

Task 1 – Literature Review (100% completed)
In the past period, we were able to perform an extensive literature review on the polyurea material and coating system for structural application, including the experimental results, material models, and numerical modeling. The summary of the literature review done to this date is attached as an appendix to this report.

Task 2 – Coupon Sample Tests (in starting phase)

We are in the process of acquiring the polyurea samples and other required equipment to perform the uniaxial tensile tests on standard ASTM dies. We have made a connection to a polyurea material supplier and applicators in the U.S. to acquire the polyurea of suitable mechanical properties for the research.

Summary of progress:

Percentage of completed work: 20%

Percentage of remaining work: 80%

Appendix: Literature Review Summary

A1. Introduction:

Polyurea is an elastomeric polymer formed by the chemical reaction of isocyanate and polyamine under high temperature and pressure. It has a chain-like structure that accounts for its high elasticity and durability. To apply polyurea coating, a pneumatic device is used to mix the isocyanate and amine components under controlled temperature and pressure and the resulting coating is sprayed on the application surface [6].

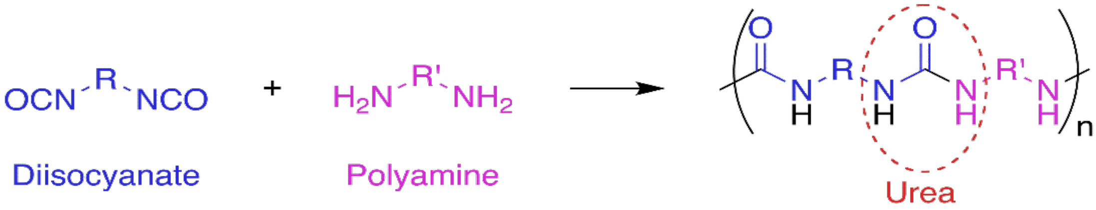

Fig A1: Polyurea component [7]

Polyurea coating has important applications for blast resistance and bulletproofing in military defense as the material can absorb and dissipate high-rate energy. The material has a local phase shift that enables it to absorb energy without permanent damage. Moreover, the material has high durability, chemical resistance, and weathering resistance that make it suitable for civil applications. Owing to its high moisture resistance, polyurea has been extensively used as a waterproofing coating and sealant. Its good abrasion resistance, strong adhesion to various construction materials [8], and corrosion resistance make it a suitable protective coating. Mechanical properties of the polyurea such as high tensile strength, ductility, high tensile stiffness, and impact resistance provide potentials for its use as strengthening material for structural applications.

Several experimental researches have been conducted to understand the behavior of polyurea under different loading conditions, to establish their mechanical properties, and to develop predictive numerical models. The studies on polyurea technology are summarized in the following sections.

A1.1. Polyurea material properties and analytical modeling studies

The study by Beyer et al.(1997) [4] assessed the compressive strength, stiffness, and ductility of polyurea sprayed concrete cylinders subjected to accelerated environmental conditions. Three different concrete mixes: High strength Light Weight Concrete (LWC), High Strength Concrete (HSC), and Normal Strength Concrete (NSC) were used to make 4in dia. x 8in high cylinder specimen. They were tested for axial compressive strength after being subjected to freeze and thaw cycles and deicing attacks. Upon examining the results showed that polyurea coating provides good durability, adhesion, confinement of fragments, and ductility enhancement.

The work by Yi et al. (2006) [9] studied the rate-dependent stress-strain behavior of the polyurea and polyurethanes by dynamic mechanical analysis, uniaxial compression testing in both the quasi-static and high strain rate loading ranging from 10^{-3}-10^{4} s^{-1}. The polyurea and the polyurethanes showed rate-dependent nature. The polyurea show behavioral transition from a rubber-like material at lower strain rates to leather-like material behavior at higher strain rates. This was caused due to the intermolecular interaction of the polymer. Similar observations of the transition of the polyurea from rubbery nature to leathery nature and strain rate dependency that accounts for the change in yield were made by Sarva et al. (2007), Raman et al.(2013), and Wang et al. (2019) [10]–[12]. They studied uniaxial compressive and tensile stress-strain behavior under low to high strain rates.

During the research by Holzworth et al. (2013) [13] seven polyurea materials were prepared by varying the ratio of isocyanate to amine (95% to 120%) then tested to determine thermal properties and characterize dynamic mechanical properties. The work showed how the increase in the isocyanate content increased the stiffness of the polyurea material and depicted how the content of the isocyanate component varied the thermal and mechanical properties of polyurea.

Research done by Tripathi et al. (2020) [14] established a correlation between strain rate sensitivity and the viscoelastic properties of polyurea by using dynamic mechanical analysis. The research showed polyurea with the lowest crosslinker content exhibited lower tensile strength but a higher strain rate sensitivity.

Research conducted by Mohotti et al. (2014) [15] proposed a strain rate-dependent constitutive material model to predict the nonlinear hyperelastic behavior of polyurea under high strain rate conditions. The proposed model named Rate Dependent Mooney Rivlin (RMDR) model was a derivative of the original Mooney Rivlin (MR) model obtained by introducing strain rate dependent parameters. RMDR model only requires evaluating one set of the material parameter at a specific strain rate but in the case of the MR model, one is required to derive a different set of material parameters for each strain rate. The study was supported by experimentation on polyurea samples under uniaxial tension at predefined strain rates ranging from $20s^{-1}$ to $400s^{-1}$. Similar research by Wang et al. (2019) [12] performed uniaxial tension and compression test to analyze the stress-strain behavior of the polyurea for strain rates ranging from 0.001 s^{-1} to 7000 s^{-1} and proposed a modified rate-dependent constitutive model based on nine parameters MR model that gave a better prediction of mechanical properties at low to high strain rates.

A study to understand the effect on the mechanical behavior of polyurea material due to the combined effect of the temperature and pressure changes was done by Nantasetphong et al. (2016) [16]. A numerical model incorporating the effect of the pressure and temperature variation was proposed based on Williams-Landel-Ferry (WLF) equation and the free volume concept. The model proposed showed good agreement with the pressure shift factor data results of the confined compression test of polyurea.

The work by Guo et al. (2016) [17] evaluated the compressive behavior of two types of polyurea under uniaxial stress test performed at the temperature range of -40°C to 20°C and the strain rate range of 0.001 s^{-1} to 12000 s^{-1}. The results of this work showed uniaxial compressive stress-strain curves are rated dependent, nonlinear and the dynamic mechanical behavior is sensitive to temperature. The rate dependency and the temperature effect decreased under confining pressure. Based on the findings visco-hyperelastic constitutive model is established to define the mechanical behavior of polyurea over a range of temperature and strain rates.

A new three-dimensional visco-hyperelastic constitutive model was proposed by Guo et al. (2017) [18] derived based on thermodynamic methods. The new model superposed the effect of viscoelasticity and hyperelasticity and accounts for the rate-dependent effect on polyurea mechanical properties.

A1.2. Polyurea coated member performance under the blast or impact loading conditions

Along with the understanding of polyurea material properties and development of the numerical models, researches on its performance under the monotonic, cyclic, blast, and impact loading conditions and its practical applications have been done in the past.

The study conducted by Davidson et al.(2004) [19] evaluated the polyurea polymer retrofitted masonry walls under blast loading. Polyurea coating was investigated as a retrofit material and blast fragmentation confinement material. The results of the explosive testing showed polyurea coating is effective in increasing blast resistance, containment of the fragments of walls.

The research conducted by Hrynyk and Myers (2007) [2] investigated the out-of-plane behaviors of URM arching walls reinforced by polyurea and glass fiber reinforced polymer (GFRP). URM walls are brittle under out-of-plane blast loading. However, the use of polyurea and GFRP retrofit increased in out-of-plane loading capacity and energy dissipation capacities. The retrofits reduced or prevented the masonry debris scatter upon collapse.

The work by Iqbal et al. (2018) [20] assessed the effect of polyurea coating application with variation in type and amount of chain extender in the concrete tiles under blast loading. Polyurea-coated concrete tiles were able to withstand higher pressure due to blast or shock. The study showed that the mechanical property of the polyurea can be tuned by introducing chain extenders that increase the formation of H bonds and enhance blast resistance.

Tests with polyurea sprayed on plane reinforced concrete panels with/without fibers [21], as a helmet suspension pad material [22], on high-performance cementitious composites [23], and steel plates [24] under the action of blast or impact loading have been done. These researches point to the same conclusion that polyurea is an excellent material for application as a blast retrofit and shows effective containment of the fragments and debris of the confined material.

A1.3. Polyurea coating performance for structural member strengthening

Despite elastomeric polymers such as polyurea having high tensile strength, high strain capacity, and good durability, we have seen very few applications of polyurea for structural strength.

During the research performed by Greene et al.(2013) [1], flexure and the shear tests on the beams specimens sprayed with polyurea with/without chopped fibers. Eight 203mm X 305 mm reinforced concrete beam specimens were fabricated. Beam length of 2438mm was adopted for flexure and 3658mm for shear. Six out of eight beams were sprayed with polyurea only or with chopped E glass fiber mixed with polyurea on the sides and the bottom with variation in thickness and fiber content. The beams were then tested on flexure and shear. Results showed that the polyurea coating of 6mm thickness increased the ultimate capacity of the beam in flexure by 23.8%. Polyurea showed effectiveness in containing the fragments during the concrete failure.

The experimental work by Marawan et al. (2015) [3] investigated the shear and flexural behavior of RC beams strengthened with the polyurea coating system. Six RC beams were cast for the flexure test out of which four beams are 1600 mm long and two are 3200 mm long. Ten RC beams were cast for shear test out of which four beams are without shear reinforcement and 1700 long, four beams with shear reinforcement and 1700mm long, and two beams with shear reinforcement are 3200mm long. All the reinforced concrete beams were of size 120mm X 250 mm coated with U-shaped polyurea leaving the top clear and the thickness of polyurea range from 2mm to 6mm. Results showed an increase in flexural capacity by 19.4% in shorter beams and 11.2% in longer beams for 6 mm thick polyurea spray. Additional shear capacity of 42.5% in shorter beams and 28.2% in longer beams were added by the 6 mm thick polyurea coating. The coating provided large ductility during concrete failure as well.

The research conducted by Parniani and Toutanji (2015) [25] examined the behavior shown by RC beams sprayed with polyurea under monotonic and fatigue loading. Five RC beams of size 102mm X 152mm and 1829 mm long were made. Three beams - one naked control beam, one with 2.5 mm thick polyurea, and the other with 5mm thick polyurea - were tested under monotonic loading of 1.5mm/min rate. Two beams - one with 2.5 mm thick polyurea and the other with 5mm thick polyurea - were tested under sinusoidal cyclic loading with a load ratio of 0.2. Results showed an increase in flexural capacity by 17.2% and 9.2% for 2.5 mm and 5 mm thick polyurea spray respectively. The coating improved the ductility of the beams. A theoretical model for the cyclic loading condition was proposed that showed satisfactory results for midspan load-deflection for less than one million loading cycles.

Some studies done on polyurea integrated with different fibers show a significant increase in the flexural strength, shear capacity, and ductility of concrete members [1][26]–[28].

Studies on polyurea sprayed on tensile strength of concrete slabs [29], crushing strength of concrete rings [30], and compressive strength of columns [31] show that polyurea could aid in improving the strength of the concrete members.

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