SMAR 2017 – Fourth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2017

Flexural Response of RC Beams Strengthened using UHPFRC Panels Epoxied to the Sides

M. A. Al-Osta[1], M. K. Rahman[1], M. N. Isa[1] and M. H. Baluch[3]

[1] King Fahd Univ. of Petroleum & Minerals, Dhahran, Saudi Arabia

ABSTRACT: Several new types of concrete have emerged in the past two decades with practical applications such as self-compacting concrete and Ultra-high Performance Concrete (UHPC). These new concretes have helped to overcome several shortcomings of the normal or conventional concrete. Precast panels made with ultra-high performance concrete with steel fiber reinforcement (UHPFRC) epoxied to the sides of an existing reinforced concrete beam is proposed to enhance the strength and ductility of the beams. This paper presents the results of a 3-D finite element model (FEM) of the strengthened beam using non-linear finite element software ABAQUS. The FE model was validated using previous experimental work carried out by the authors with a good accuracy. A parametric study was conducted to investigate the flexural response of RC beams strengthened with different thicknesses of UHPFRC precast panels epoxied to various sides of the beam. The results showed that the ductility of RC beams strengthened by UHPFRC enhances with an increase in the thickness of panels for various strengthening configurations.

1 INTRODUCTION

Concrete is the vital material in construction of many structures around the world. The reinforcing steel is used to compensate some weakness in concrete, which characterized as a brittle material. Reinforced concrete (RC) industry is a combination between the science and engineering. RC structures exhibited excellent performance in terms of mechanical properties, durability, and economic. However, over the time, the RC structures have suffered from many problems such as corrosion of steel reinforcement, increased live loads, exposure to harmful aggressive environments, freeze-thaw cycles and may change in the usage of the structures. Therefore, one of the most challenges in civil engineering is how to repair or strengthen these structures.

Many researches have been conducted on the rehabilitation of RC structures and new developed concretes have been invented to restore and improve the damaged members. The performance criteria of such concretes must meet the code requirements and standards. Low cost, efficiency, safety, compatibility, structural behavior, bond strength, stiffness, durability are the most important properties of any repaired material.

Martinola et al. (2010) studied the effect of fiber reinforced concrete in strengthening and repair of full-scale RC beams. Both experimental and numerical techniques were adopted in this investigation. The results demonstrated that the proposed technique enhanced the behavior of strengthened RC beams at both ultimate and serviceability limit state. Furthermore, a good improvement in the durability of the beams was observed due to using of HPFRC jacket. Mahmud et al. (2013) investigated the size effects of ultra-high performance steel fiber reinforced concrete (UHPFRC) on the flexural strength of the beams. Mahmud et al also developed a numerical modeling using ABAQUS software. Both experimental and numerical results showed that the size-effect in the flexural strength of the beams is almost negligible. Chalioris et al. (2014)

investigated the use of thin reinforced self-compacting concrete (SCC) for strengthening of conventional RC beams. The results showed an increasing in the strength with improved in the ductility and favorable failure behavior. It was concluded that the high strength self-compacting concrete (SCC) is a quick option for rehabilitation or strengthening the existing RC beams. Ruano et al. (2015 conducted an experimental work and a numerical modeling of behavior of RC beams strengthened in shear with high-performance self-compacting concrete. Both experimental and numerical results demonstrated that the fiber content not only preventing debonding from concrete substrate but also increased the load bearing capacity of strengthened RC beams. Lampropoulos et al. (2016) investigated the efficiency of using UHPFC for strengthening of conventional RC beams. Different types of configuration of UHPFC layers were used, in the tensile, in the compressive side and with three-side jacket. The results showed that a significant moment increment when three sides jacket was used. Al-Osta et al. (2017) studied numerically and experimentally the behavior of reinforced concrete (RC) beams strengthened with layers of UHPFC that had a thickness of 30 mm only. Different types of configuration of UHPFC layers were used, bottom side, 2 sides and 3 sides. The results showed that beams strengthened on three sides showed the highest capacity enhancement

The need of retrofitting the existing structures has been enormous in last years. The most popular technique is using the Carbon Fiber Reinforced Polymer (CFRP) laminates for upgrading the deteriorated structures. CFRP possess desired properties such as high-strength, corrosion protection, ease to apply and minimal size change. Beside all these advantages, CFRP system has some shortcomings, which mainly related to the bond and the incompatibility problems. Therefore, in this study, the UHPFRC panels epoxied with different thickness to the sides of RC beams were numerically investigated.

2 OUTLINE OF EXPERIMENTAL TEST PROGRAM

To validate the developed model, simply supported RC beams are tested under four-point loading setup as shown in Figure 1. The beams were with dimensions as shown in Figure 2. LVDT was used to measure vertical deflection at midspan. Data from the experimental work and finite element model were compared.

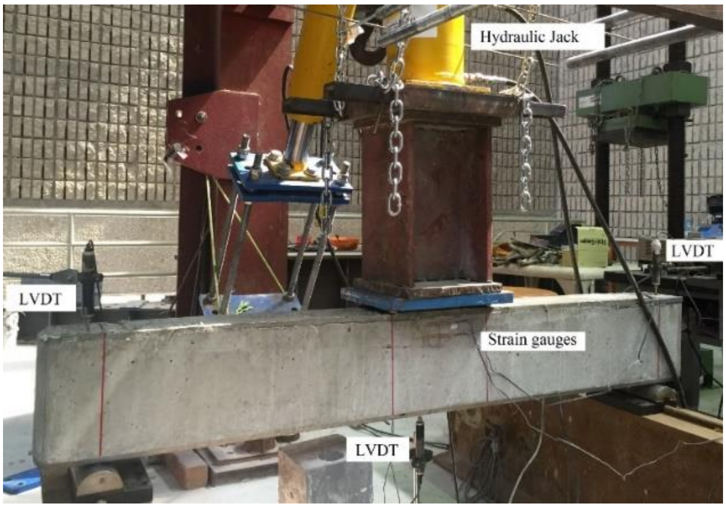


Figure 1: Beam test set-up

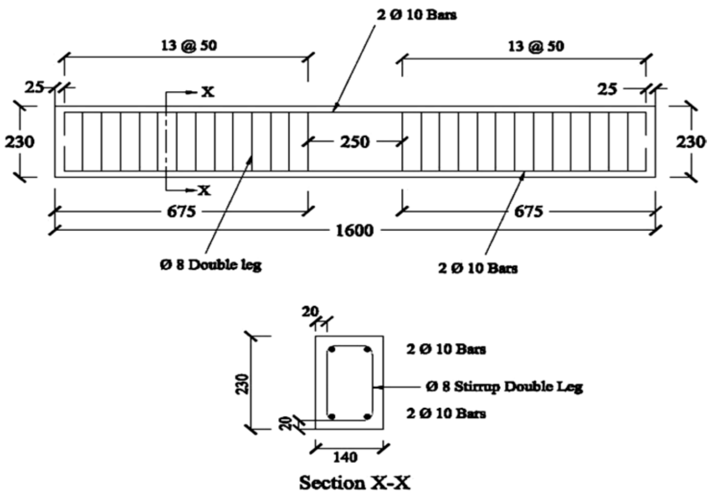


Figure 2. Geometry and details of concrete beam specimens (all dimensions in mm) (Al-Osta, Isa et al. 2017)

2.1 Using Epoxy Adhesive

In this method, UHPFRC strips were produced by casting fresh UHPFRC separately in molds having the desired dimension (i.e. corresponding to the dimension of the beam surface for which it will be attached to) as shown in Figure 3a. The strips were demoulded after 24hrs and moist cured for 28 days inside a curing tank. After curing, the strips were bonded to the desired beam surfaces using the epoxy adhesive “FOSROC NITOBOND EP” The bond is air cured for 7 days an air temperature of between 25 - 31°C (Figure 3b)

(a) (b)

Figure 3: (a) UHPFRC strips (b) Strengthened beams specimens using epoxy adhesive bonding

2.2 Bond Tests

To ensure adequate bond strength between UHPFRC and normal concrete substrates, two types of bond strength test were carried out i.e. split cylinder tensile strength test and slant shear test on composite UHPFRC-normal concrete cylinders in accordance with ASTM C496 and ASTM C882, respectively. The UHPFRC was bonded to the normal concrete (NC) substrate as shown in Figure 4 using epoxy adhesive. As shown un Figure 4, the failure occurs within the concrete substrate which indictes that a good bond between UHPFRC and normal concrete. The average values of split cylinder tensile strength and slant shear strenght of tested spemines were 5.85 MPa and 23.15 MPa, respectively. Therefore, the split cylinder tensile strength of specimens fall under the category of "Excellent bond quality" (i.e. if tensile bond strength ≥ 2.1 MPa) as quantified by (Sprinkel and Ozyildirim 2000) . In addtion, the slant shear strength for specimens indicated adequate bond strength in accordance to (Chynoweth, Stankie et al. 1996) which specifies a slant shear strength of ≥ 20.7 MPa at 28 days. These results showed that UHPFRC has excellent bonding with surface of the concrete substrate.

(a) (b) (c)

Figure 4: (a) Half split cylinders (b) Slant cut cylinders (c) Split cylinder tensile strength bond test

3 FINITE ELEMENT MODELLING

A 3D non-linear FE model of RC beams after and before strengthening with UHPFRC layers was developed and validated with pervious experimental results. Thereafter, a parametric study was conducted to investigate the effect of thickness of UHPFRC layer used on the over whole behavior of the RC beams. The non-linear FE software ABAQUS was used to numerically simulate the flexural behavior of RC beams strengthened with UHPFRC layers. The elastic behavior of the materials was modeled by defining the elastic properties, Modulus of Elasticity$E = 34\ GPa$; Poisson's ratio $\mathcal{V} = 0.15\ for\ NC\ and\ E = 46\ GPa$; $\mathcal{V} = 0.18\ for\ UHPC$. For the nonlinear behavior for both normal and UHPFRC concrete, the Concrete Damage-Plasticity Model (CDPM) was used (Lubliner, Oliver et al. 1989); (Lee and Fenves 1998) and (Rodríguez Soler, Martinez Cutillas et al. 2013). In CDPM, the materials were defined by inputting the parameters shown in Table 1 as well as the nonlinear experimental data given by the authors (Al-Osta, Isa et al. 2017). Furthermore, the CDPM model needs damage parameters d_c and d_t for compressive and tension load, respectively that can be used to identify the damage pattern and compare it with experimental work. These damage parameters can estimated by using Eqs. (1) and (2). For steel rebars and stirrups, an elastic-perfectly plastic relationship whose parameters were obtained by experimental testing$f_y = 590MPa, E = 200GPa$.

In this paper, to overcome convergence problems associated from the cracking of concrete, dynamic explicit method was used.

Table 1: Concrete damage plasticity model parameter for concrete and UHPFRC (Al-Osta et al. 2017)

Ψ (°)	*Eccentricity*	σ_{b0}/σ_{c0}	K	Viscosity parameter
Normal Concrete (NC)				
36	0.1	1.16	0.667	0
UHPFRC				
36	0.1	1.16	0.667	0

where:

$\frac{\sigma_{b0}}{\sigma_{c0}}$ is the ratio of initial biaxial compressive yield stress to initial uniaxial compressive yield stress;

K is the ratio of the second stress invariant on the tensile meridian (TM) to that on the compressive meridian (CM). Ψ is dilation angle.

Concrete compression and tension damage parameters given by Birtel and Mark (2006) is used in the model and are given as:

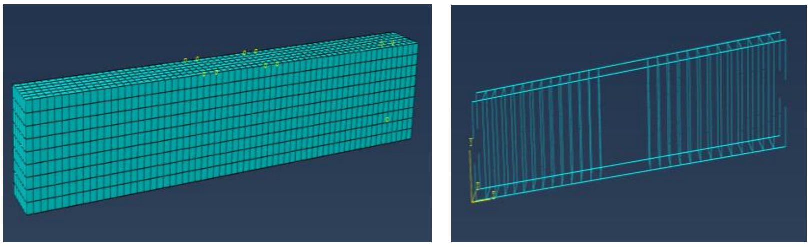
$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\epsilon_c^{pl}\left(\frac{1}{b_c}-1\right)+\sigma_c E_c^{-1}} \qquad d_t = 1 - \frac{\sigma_t E_c^{-1}}{\epsilon_t^{pl}\left(\frac{1}{b_t}-1\right)+\sigma_t E_c^{-1}} \tag{1}$$

where: d_c = Concrete tension damage parameter; σ_c = Compressive Stress; E_c = Concrete elastic modulus; ϵ_c^{pl} = Plastic strain corresponding to compressive stress; b_c = constant with range $0 < b_c < 1$.

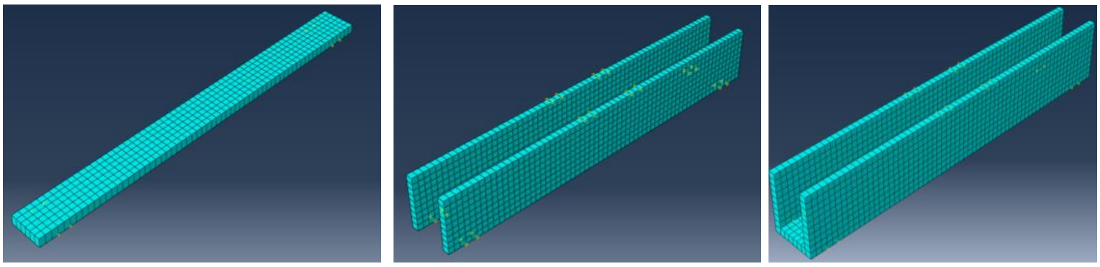
d_t = Concrete tension damage parameter; σ_t = Tensile Stress; ϵ_t^{pl} = Plastic strain corresponding to tensile stress; b_t = constant with range $0 < b_t < 1$.

3.1 Geometry Model

For both normal and UHPFRC concrete, a 3D- 8noded linear brick element was used as shown in Figure 5. This type of element can be used for both linear analysis and non-linear analysis. For the steel rebars and stirrups, a 2-noded linear 3D truss element was used. The interaction between between between the UHPFRC and normal concrete (NC) is considered as perfect bond. This assumption was based on the test made for the bond between the UHPFRC layers and normal concrete as reported in Section 2.2. In addtion,the experimental test of the strengthened beams showed that no debonding has been observed between the NC and UHPC.



(a) Concrete elements (b) Steel reinforcing bars elements



(c) UHPFRC bottom side (d) UHPFRC 2-sides (e) UHPFRC 3-sides

Figure 5: Meshed beam specimen

3.2 Validation of finite element model

The finite element results of the model developed was validated with the results obtained from the experimental work. Figure 6 demonstrates that the FEM can capture the failure load and the behavior of RC beams strengthened by layers of UHPFRC. Therefore, it can be concluded that the CDPM model can be used to predict the behavior of RC beams strengthened by layers of with good accuracy.

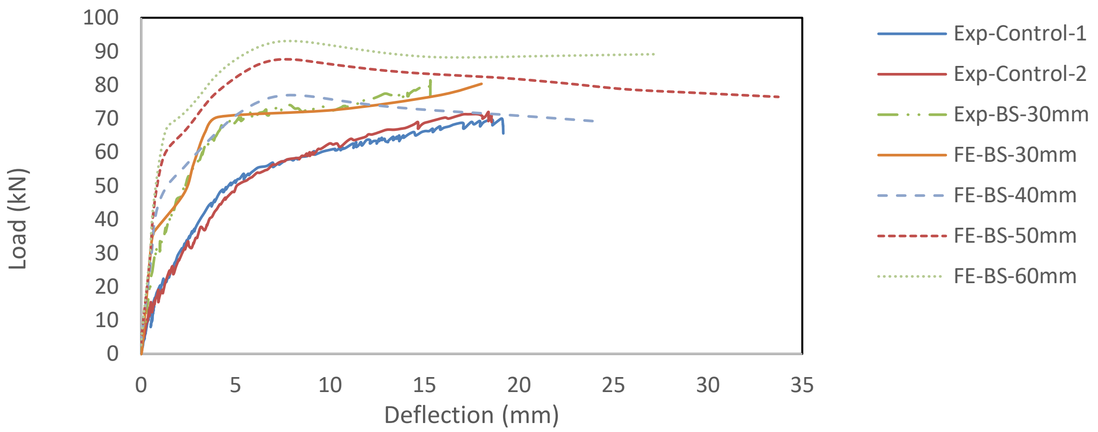
4 PARAMETRIC STUDY ON UHPFRC THICKNESS'S

The parametric study was conducted to study the effects of UHPFRC thickness's on the behavior of RC beams strengthened with different configurations of UHPFRC layers. Figure 6a shows the load vs. deflection of the RC beams strengthened with different thickness of UHPFRC in the bottom side only (30 mm, 40 mm, 50 mm, and 60 mm). It can be seen that the capacity and ductility of the beam enhanced with increasing the thickness of UHPFRC. The failure load of beam strengthened with 60 mm of UHPFRC increased by 29 % as compared to the control beam. In the case of $EP - 2S$, the beam with thickness of UHPFRC 30 mm showed load increased and ductile nature of failure as shown in Figure 6b. However, EP-2S with thickness of UHPFRC that is more than 30 mm, the load increased with a slight increasing in stiffness, followed by a sudden fall in load in a softening mode, indicating a significantly less ductile failure as compared to RC-Control, RC-EB-BOTS and RC-EB-2S-30mm. The brittle nature of failure of EP-2S with thickness of UHPFRC that is greater than 30 mm may be attributed to the crushing of the UHPFRC at strain levels near 0.0015 to 0.002.
In case of EP-3S with thickness 30 mm, similar behavior has been observed as in case of EP-2S, whereas EP-3S with thickness that is more than 30 mm showed similar behavior as in case of strengthening with bottom side as shown in Figure 6c.

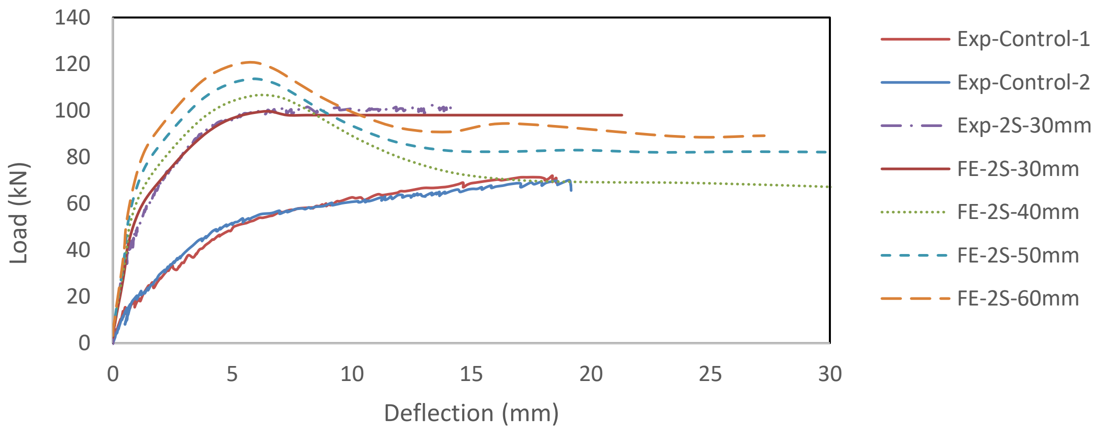
5 CONCLUSIONS

Based on the numerical and parametric study investigations of the flexural behavior of RC beams strengthened with UHPFRC, the following conclusions could be drawn:

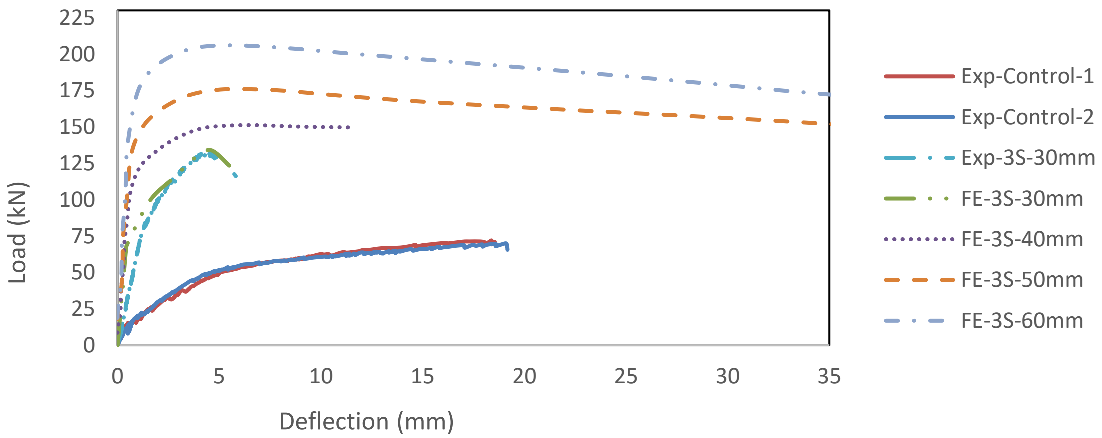
- The results of (FEM) showed good agreement with the experimental test results. Therefore, it can be concluded that the CDPM can be used to predicted peak load and load-deflection behavior of RC beam strengthened with UHPFRC.
- Beam strengthened on its bottom side showed least capacity enhancement, whereas beams strengthened at the two or three sides showed the higher enhancement for UHPFRC strengthening configuration.
- Load increased and ductile nature of failure is observed for the beam strengthened with thickness of UHPFRC that is 30 mm.
- As the thickness of UHPFRC layers for the two-side configuration increases, the load increases with a slight increasing in stiffness, followed by a sudden fall in load in a softening mode, indicating a significantly less ductile failure as compared to control sample. The brittle nature of failure of EP-2S with thickness of UHPFRC that is greater than 30 mm may be attributed to the crushing of the UHPFRC at strain levels near 0.0015 to 0.002.
- Beam strengthened on three sides with UHPFRC thickness more or equal than 30 mm showed big enhancement in the capacity as well as in the ductility



(a) RC-BOT SJ



(b) RC-2 SJ



(c) RC-3 SJ

Figure 6: Experimental and FE load deflection behavior of RC beams strengthen with UHPFRC

6 ACKNOWLEDGEMENT

This study was made possible with the support of Department of Civil and Environmental Engineering and Research institute at King Fahd University of Petroleum and Minerals.

7 REFERENCES

Al-Osta, M., M. Isa, M. Baluch and M. Rahman (2017). Flexural behavior of reinforced concrete beams strengthened with ultra-high performance fiber reinforced concrete. *Construction and Building Materials* 134: 279-296.

Birtel, V. and P. Mark (2006). Parameterised finite element modelling of RC beam shear failure. *ABAQUS Users' Conference*.

Chalioris, C. E., G. E. Thermou and S. J. Pantazopoulou (2014). Behaviour of rehabilitated RC beams with self-compacting concrete jacketing–Analytical model and test results. *Construction and Building Materials* 55: 257-273.

Chynoweth, G., R. R. Stankie, W. L. Allen, R. R. Anderson, W. N. Babcock, P. Barlow, J. J. Bartholomew, G. O. Bergemann, R. E. Bullock and F. J. Constantino (1996). Concrete repair guide. *ACI committee, concrete repair manual* 546: 287-327.

Lampropoulos, A., S. A. Paschalis, O. Tsioulou and S. E. Dritsos (2016). Strengthening of reinforced concrete beams using ultra high performance fibre reinforced concrete (UHPFRC). *Engineering Structures* 106: 370-384.

Lee, J. and G. L. Fenves (1998). "Plastic-damage model for cyclic loading of concrete structures." *Journal of engineering mechanics* 124(8): 892-900.

Lubliner, J., J. Oliver, S. Oller and E. Onate (1989). A plastic-damage model for concrete. *International Journal of solids and structures* 25(3): 299-326.

Mahmud, G. H., Z. Yang and A. M. Hassan (2013). Experimental and numerical studies of size effects of Ultra High Performance Steel Fibre Reinforced Concrete (UHPFRC) beams. C*onstruction and Building Materials* 48: 1027-1034.

Martinola, G., A. Meda, G. A. Plizzari and Z. Rinaldi (2010). Strengthening and repair of RC beams with fiber reinforced concrete. *Cement and Concrete Composites* 32(9): 731-739.

Rodríguez Soler, J., F. J. Martinez Cutillas and J. Marti Rodriguez (2013). Concrete constitutive model, calibration and applications. 2*013 SIMULIA Community Conference*.

Ruano, G., F. Isla, D. Sfer and B. Luccioni (2015). Numerical modeling of reinforced concrete beams repaired and strengthened with SFRC. *Engineering Structures* 86: 168-181.

Sprinkel, M. M. and C. Ozyildirim (2000). Evaluation of high performance concrete overlays placed on Route 60 over Lynnhaven Inlet in Virginia. *Final Report, Virginia Department of Transportation*.