# Transportation Consortium of South-Central States



Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

# **Cost-Effective Methods to Retrofit Metal Culverts Using Composites**

Project No. 17STUNM03 Lead University: University of New Mexico

> Final Report June 2019

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| One of the current pressing problems<br>These metal culverts typically are dest<br>than 30 years. A Glass Fiber Reinforce<br>liner for complete repair and rehabilit<br>mainly because of the corrosion free re<br>laboratory scale three-point bending t<br>element model was developed to provi<br>corrosion on the mechanics of the retri-<br>be used to design GFRP section for re-<br>developed to conduct a cost-benefit and<br>technologies. | for all DOTs is the cor<br>igned for a life of 50 ye<br>ed Polymers (GFRP) p<br>ation of the corroded m<br>nature of the GFRP man<br>est was conducted to ter<br>vide inference on the m<br>rofitted pipe. The FE m<br>etrofitting an existing con<br>nalysis of the proposed | rosion-oriented deteriora<br>ears. However, corrosion<br>pipe section has been evan<br>tetal culvert with an expe-<br>terial. A comprehensive<br>est the composite action of<br>echanics of the GFRP-C<br>odel was verified with e<br>ulvert in the field. A Life<br>retrofitting technique ar | ation of existing meta<br>n is making them last<br>luated as a fit-in GFI<br>ected life of 75 years<br>rehabilitation method<br>of the steel-GFRP see<br>MP section and the e<br>xperimental observat<br>e Cycle Cost Analysi<br>ad compare it with ot | ll culverts.<br>no longer<br>RP profile<br>. This is<br>dology and<br>ction. A finite<br>effect of<br>cions and will<br>s model was<br>her existing |  |
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|   | SI* (MODER  | N METRIC) CONVER   | SION FACTORS   |   |
|---|---|--|--|---|
|   | APPR  | OXIMATE CONVERSIONS  | TO SI UNITS  |   |
| Symbol  | When You Know   | Multiply By  | To Find  | Symbol  |
|   |   | LENGTH   |  | -   |
| in  | inches  | 25.4   | millimeters  | mm  |
| ft  | feet  | 0.305  | meters   | m   |
| yd  | yards   | 0.914  | meters   | m   |
| mi  | miles   | 1.61   | kilometers   | km  |
| 0   |   | AREA   |  | 0   |
| in  | square inches   | 645.2  | square millimeters   | mmٍ²  |
| ft <sup>2</sup>   | square feet   | 0.093  | square meters  | m <sup>2</sup>  |
| yd²   | square yard   | 0.836  | square meters  | m <sup>2</sup>  |
| ac  | acres   | 0.405  | hectares   | ha  |
| ITH   | square miles  | 2.59   | square kilometers  | KIII  |
| 0   | 0.1.1   | VOLUME   |  |   |
| fi oz   | fluid ounces  | 29.57  | milliters  | mL  |
| gai<br># <sup>3</sup>   | gallons<br>cubic foot   | 3.785  | litters  | L<br>m <sup>3</sup>   |
| vd <sup>3</sup>   | cubic vards   | 0.020  | cubic meters   | m <sup>3</sup>  |
| yu  | NOT   | E volumes greater than 1000 L shall be   | shown in m <sup>3</sup>  |   |
|   |   | MASS   |  |   |
| 07  | 010000  | 28 35  | grams  | a   |
| lb  | pounds  | 0 454  | kilograms  | y<br>ka   |
| T   | short tons (2000 lb)  | 0.907  | megagrams (or "metric ton")  | Ma (or "t")   |
|   |   | TEMPERATURE (exact deg   |  |   |
| °F  | Fahrenheit  | 5 (F-32)/9   | Celsius  | °C  |
|   |   | or (F-32)/1.8  | Colorad  | Ũ   |
|   |   |  |  |   |
| fc  | foot-candles  | 10.76  | lux  | ly.   |
| fl  | foot-Lamberts   | 3 426  | candela/m <sup>2</sup>   | cd/m <sup>2</sup>   |
|   |   | FORCE and PRESSURE or SI   | RESS   | 00,111  |
| lbf   | n a cur alf a na a  |  |  | N   |
|   | DOUDDITOTO  | // //5   | nownone  |   |
| lbf/in <sup>2</sup>   | poundforce per square ir  | 4.45<br>nch 6.89   | kilopascals  | kPa   |
| lbf/in <sup>2</sup>   | poundforce per square ir  | 4.45<br>nch 6.89   | kilopascals  | kPa   |
| lbf/in <sup>2</sup>   | poundforce per square in<br>APPRO   | A.45<br>6.89<br>XIMATE CONVERSIONS FF  | kilopascals  | kPa   |
| bf/in <sup>2</sup><br>Symbol  | poundiorce<br>poundforce per square ir<br>APPRO2<br>When You Know   | A45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By  | ROM SI UNITS   | kPa<br>Symbol   |
| Ibf/in <sup>2</sup>   | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know  | A45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH  | ROM SI UNITS<br>To Find  | kPa<br>Symbol   |
| Bolin <sup>2</sup><br>Symbol<br>mm  | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know<br>millimeters   | A.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039  | ROM SI UNITS<br>To Find  | kPa<br>Symbol   |
| Symbol<br>mm  | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know<br>millimeters<br>meters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>4.00  | inches<br>feet   | N kPa<br>Symbol   |
| mm<br>m<br>m<br>br  | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilemeters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.631   | inches<br>feet<br>yards  | N<br>kPa<br>Symbol<br>in<br>ft<br>yd  |
| mm<br>m<br>km   | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>ABEA   | inches<br>feet<br>yards<br>miles   | in<br>ft<br>yd<br>mi  |
| mm<br>m<br>km   | millimeters<br>meters<br>kilometers   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.040  | inches<br>feet<br>yards<br>miles   | N<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi  |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup>  | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square millimeters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764   | inches<br>feet<br>yards<br>miles<br>square inches<br>square fact   | N<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>t <sup>2</sup>   |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>m <sup>2</sup>  | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195  | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square yards   | N kPa<br>Symbol   |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>m <sup>2</sup><br>ba  | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47  | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square feet<br>square yards<br>acres   | N kPa<br>Symbol   |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup>   | poundiorce<br>poundforce per square ir<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square kilometers  | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386   | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square gards<br>acres<br>square miles  | N<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup>  |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup>   | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square kilometers  | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME   | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square yards<br>acres<br>square miles  | N<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup>  |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>mL   | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square kilometers<br>milliliters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034  | A second  | IN<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup><br>fl oz  |
| mm<br>m<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>L   | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square kilometers<br>milliliters<br>liters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034<br>0.264   | A second  | IN<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup><br>fl oz<br>gal   |
| mm<br>m<br>m<br>km<br>m<br>m <sup>2</sup><br>m <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>m<br>L<br>L<br>m <sup>3</sup>   | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square kilometers<br>milliliters<br>liters<br>cubic meters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034<br>0.264<br>35.314   | A service of the serv | N<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup><br>fl oz<br>gal<br>ft <sup>3</sup>   |
| mm<br>m<br>m<br>km<br>m<br>km <sup>2</sup><br>m <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>km <sup>2</sup><br>m<br>L<br>L<br>m <sup>3</sup><br>m <sup>3</sup>   | poundiorce<br>poundiorce per square in<br>APPRO.<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square meters<br>hectares<br>square kilometers<br>milliliters<br>liters<br>cubic meters<br>cubic meters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034<br>0.264<br>35.314<br>1.307  | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square yards<br>acres<br>square miles<br>fluid ounces<br>gallons<br>cubic feet<br>cubic yards  | N<br>kPa<br>Symbol<br>in<br>ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup><br>fl oz<br>gal<br>ft <sup>3</sup><br>yd <sup>3</sup>  |
| mm<br>m<br>km<br>mm <sup>2</sup><br>m <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>mL<br>L<br>m <sup>3</sup><br>m <sup>3</sup>  | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>hectares<br>square meters<br>hectares<br>square kilometers<br>milliliters<br>liters<br>cubic meters<br>cubic meters  | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034<br>0.264<br>35.314<br>1.307<br>MASS  | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square yards<br>acres<br>square miles<br>fluid ounces<br>gallons<br>cubic feet<br>cubic yards  | N kPa<br>Symbol<br>in ft<br>yd<br>mi<br>in <sup>2</sup> ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup><br>fl oz<br>gal<br>ft <sup>3</sup><br>yd <sup>3</sup>   |
| mm<br>m<br>m<br>km<br>m<br>km <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>mL<br>L<br>m <sup>3</sup><br>m <sup>3</sup><br>m <sup>3</sup><br>g   | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>square meters<br>hectares<br>square meters<br>square kilometers<br>milliliters<br>liters<br>cubic meters<br>cubic meters<br>cubic meters   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034<br>0.264<br>35.314<br>1.307<br>MASS<br>0.035   | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square yards<br>acres<br>square miles<br>fluid ounces<br>gallons<br>cubic feet<br>cubic yards  | N kPa<br>Symbol<br>in ft<br>yd mi<br>in <sup>2</sup> ft <sup>2</sup><br>yd <sup>2</sup><br>ac mi <sup>2</sup><br>fl oz gal<br>fl oz gal<br>ft <sup>3</sup><br>yd <sup>3</sup><br>oz   |
| mm<br>m<br>m<br>km<br>m<br>km <sup>2</sup><br>m <sup>2</sup><br>ha<br>km <sup>2</sup><br>mL<br>L<br>m <sup>3</sup><br>m <sup>3</sup><br>m <sup>3</sup>  | poundiorce<br>poundforce per square in<br>APPRO<br>When You Know<br>millimeters<br>meters<br>meters<br>kilometers<br>square millimeters<br>square meters<br>square meters<br>square meters<br>square meters<br>square meters<br>milliliters<br>liters<br>cubic meters<br>cubic meters<br>cubic meters<br>grams<br>kilograms   | 4.45<br>6.89<br>XIMATE CONVERSIONS FF<br>Multiply By<br>LENGTH<br>0.039<br>3.28<br>1.09<br>0.621<br>AREA<br>0.0016<br>10.764<br>1.195<br>2.47<br>0.386<br>VOLUME<br>0.034<br>0.264<br>35.314<br>1.307<br>MASS<br>0.035<br>2.202  | inches<br>feet<br>yards<br>miles<br>square inches<br>square feet<br>square yards<br>acres<br>square miles<br>fluid ounces<br>gallons<br>cubic feet<br>cubic yards<br>ounces<br>pounds  | N kPa<br>Symbol<br>in ft<br>yd<br>mi<br>in <sup>2</sup><br>ft <sup>2</sup><br>yd <sup>2</sup><br>ac<br>mi <sup>2</sup><br>fl oz<br>gal<br>ft <sup>3</sup><br>yd <sup>3</sup><br>oz<br>lb                                      |
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# ACRONYMS, ABBREVIATIONS, AND SYMBOLS

| AASHTO | American Association of State Highway and Transportation |
|--------|--|
|        | Officials  |
| FHWA   | Federal Highway Administration                           |
| NMDOT  | New Mexico Department of Transportation                  |
| GFRP   | Glass Fiber Reinforced Polymers                          |

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# **EXECUTIVE SUMMARY**

Metal culverts have served as a common element in highway design since the mid 1950's because of their low initial cost, ease of fabrication and simple construction method. There has been an epidemic of corrosion of metal culverts for the last decade. Such corrosion results in loss of cross-section and occasionally leads to structural failure of the culvert. Numerous failures have taken place imposing a high cost with the need to rebuild many culverts in addition to significant indirect costs associated with highway closure. While the expected life span of metal culverts is around 50 years, the literature reports that most metal culverts survived no longer than 30 years before the need for repair and retrofit specifically because of corrosion. Currently, corroded metal culverts are repaired using a corrugated steel liner with a grouting material or using shotcrete. Both techniques are still prone to corrosion and degradation as steel liners would start to corrode after coming in touch with the corroding metal culverts and shotcrete will lose its roughness with water flow. Hence, there is an immediate need to develop a cost-effective corrosion-free technique to retrofit corroded metal culverts. The proposed technique would extend the service life of metal culverts to 75 years.

Glass fiber reinforced polymers (GFRP) have become a desirable material for structural strengthening and rehabilitation in the last two decades. While corrosion free and of low weight, GFRP cost has dropped significantly with manufacturing advances. In addition, GFRP material does not require additional protective coatings or maintenance. Hence, we investigate a fit-in GFRP profile liner to completely rehabilitate the existing corroded metal culvert.

Our investigations included conducting a literature search of rehabilitation materials for metal culverts, developing a culvert database with the help of the New Mexico Department of Transportation (NMDOT) including the characteristics of existing metal culverts in New Mexico, and testing the use of GFRP for culvert rehabilitation. We examined bond issues between GFRP and metal surfaces to identify optimal methods and adhesives to bond GFRP to metal culverts. Furthermore, we conducted a laboratory load test of a full-scale metal culvert retrofitted with fit-in GFRP profile liner. Finally, during the implementation phase, design and field retrofit of a corroded metal culvert using GFRP will be conducted in collaboration with NMDOT.

# **1. INTRODUCTION**

Culverts are structures that facilitate the smooth conveyance of water without affecting the flow of water into the surrounding ecosystem. Culverts are also critical for the stability of highway infrastructure and storm sewers. Metal culverts have served as a common structural element in highway design since the mid 1950's because of their low initial cost, ease of fabrication and simple construction methods. There has been an epidemic of corrosion of metal culverts for the last decade. Such corrosion results in loss of cross-section and occasionally leads to structural failure of the culvert. Numerous failures have taken place thus imposing a high cost with the need to rebuild many culverts in addition to significant indirect costs associated with highway closure. While the expected life span of metal culverts is around 50 years, literature reports that most metal culverts survived no longer than 30 years before the need for repair and retrofit specifically because of corrosion. Currently, corroded metal culverts are repaired using a corrugated steel liner with a grouting material or using shotcrete material. Both techniques are still prone to corrosion and degradation as steel liners start to corrode after getting in touch with the corroding metal culverts and shotcrete cracks with water flow. Hence, there is an immediate need to develop a cost-effective corrosion-free technique to retrofit corroding metal culverts. The proposed technique shall enable extending the service life of metal culverts to 75-100 years.

Currently, culvert retrofits are carried out using two main techniques, i.e., slip lining and spray on lining. Slip lining is currently performed by inserting poly vinyl chloride (PVC) pipes or high-density polyethylene (HDPE) pipes with the help of slip rails and filling gaps between the host pipe and the new pipe using a grout. Though inserting PVC and HDPE pipes looks promising because of their corrosion resistance, the pipes are brittle in cold temperatures and have relatively low structural capacity. This can be an issue for retrofitting corroded metal culverts that have lost most of their structural capacity due to corrosion. Furthermore, it is difficult to use PVC and HDPE pipes for retrofitting cross sections other than those circular in shape.

Glass fiber reinforced polymer (GFRP) has become a desirable material for structural strengthening and rehabilitation in the last two decades. GFRP is corrosion free, light weight and the cost has dropped significantly with manufacturing advances. In addition, GFRP does not require additional protective coatings or maintenance. Hence, we investigate fit in GFRP profile liner to completely rehabilitate the existing corroded metal culvert. GFRP retrofitted culverts might achieve 75–100 years of life expectancy. Unlike PVC and HDPE systems, GFRP profile liner production uses filament-winding technology and thus can be fabricated in many desired shapes not limited to circles and cross-sections, and with optimized fibers' orientation to attain specific strengths. Full composite action between GFRP and steel is critical to ensure that the forces applied to the steel culvert are transferred and resisted by GFRP.

This research focuses on investigating GFRP as a potential material for retrofit of corroded metal culverts. A full-scale laboratory test of metal culvert retrofitted with fit-in GFRP profile liner is implemented. The objective of the full-scale laboratory test is to examine the ability of the GFRP technology to develop full composite action with the corroded metal

culvert and thus provide an acceptable retrofitting technology. Material characterization is conducted to allow developing a representative finite element model to simulate the retrofitted metal culvert. The finite element model is then validated with the experimental observation and then used further for future design of the retrofitting GFRP.

#### 2. OBJECTIVES

The objective of this study is to design and test a cost-effective technique for retrofitting corroded metal culverts using GFRP material. The desired outcome is that the retrofitting technique should extend the life expectancy of retrofitted metal culverts beyond 75 years. The study objective was achieved through analysis, design and mechanical testing of GFRP retrofitting alternatives to ensure a safe and corrosion-free metal-GFRP composite culvert. Furthermore, all tasks were conducted in close collaboration with the New Mexico Department of Transportation (NMDOT) to ensure that the design of the GRFP retrofitting technique meets New Mexico needs.

To achieve the above objectives, in the current study, a comprehensive laboratory full scale retrofit technique methodology was developed using GFRP as slip lining material and an epoxy-based grout to bond the GFRP profile to the metal culvert pipe. The retrofitted steel-GFRP-grout section was tested under three-point bending configuration to test the composite action. Furthermore, a complete material characterization of GFRP material and the epoxy grout material was conducted. The GFRP was tested in two configurations, i.e., on-axis (0° fiber orientation) and off-axis (45° fiber orientation) under direct tension and compression. The epoxy grout was tested under direct tension and compression. The material properties of both GFRP and epoxy grout were used to develop a finite element model developed to simulate the behavior of the retrofitted metal culvert under realistic traffic loads. The finite element model is then validated using experimental observations.

In the field, corroded culverts can be in different forms. Some of the sections may have complete loss of cross section in the bottom flow path or a partial loss in cross section. Based on the specific soil type in the field location, the straining actions on the culvert may vary. Design shall therefore take the above into account. The finite element model can then be updated with field conditions and used for the design of the GFRP system to be used for this specific field retrofitting. The GFRP section may be optimized for the thickness to achieve an economic design and on the lay-up to meet performance requirements.

# **3. LITERATURE REVIEW**

#### **Corrugated metal culverts**

Metal culverts are flexible long spanning piped structures that facilitate the smooth conveyance of water bodies without affecting the structure of these water bodies and the ecosystem. Typically, these structures are used for storm sewers, underpasses and railway and highway bridges. These piped structures are prefabricated using curved metal plates and

connected using bolts [1]. Later, these piped structures are buried with a backfill for easy transfer of loads and to provide stability for the culvert structure. Typically, metal culverts are made of steel and aluminum. Because of ease of installation and low cost of fabrication, metal culverts have gained wide acceptance since the mid 1950's. Metal culverts also have been fabricated in different desired shapes with constant radius circle, ellipse in horizontal or vertical directions and arched-pipe as presented in **Figure 1** [2].



Figure 1: Different profiles for metal culverts [2]

Corrosion of metal culverts, as shown in **Figure 2**, has been a considerable challenge as it excessively lowered their life expectancy and significantly affected their serviceability. The literature shows that the life expectancy for metal culverts is around 50 years [3]. However, heavy corrosion dropped this life expectancy to lower than 30 years creating significant financial overburden on metal culverts [3]. A Transportation Research Board (TRB) report in 2004 clearly indicated that failure of metal culverts has been significantly increasing all over the country. Failure of metal culverts is a relatively expensive event. The high cost of rebuilding metal culverts is not only related to materials and construction cost, but also to costs associated with closure of roads to reconstruct failed culverts and related to traffic delay [4].



Figure 2: Corroded metal culvert [5]

Finally, engineers prefer to retrofit existing culverts rather than replace them because of the complexity associated with un-backfilling, deconstruction and reconstruction and rebackfilling. Two promising techniques listed in the literature are now used to retrofit metal culverts. This includes using a metal liner inside the metal culvert and shotcrete lining [4]. The challenge is that the metal liner is still prone to corrosion and shotcrete loses cross-section due to water flow abrasion. There is an urgent need to develop cost-effective strategies to retrofit corroding metal culverts that are corrosion free and require minimal maintenance.

# **Fiber-Reinforced Polymers**

Fiber reinforced polymers (FRP) are polymeric matrix typically polyester, vinyl ester, and epoxy reinforced with synthetic fibers being glass, carbon, basalt or aramid fibers. With improved manufacturing techniques and because of significant low cost, glass fiber reinforced polymers (GFRP) have emerged as a desirable material for structural applications. GFRP is essentially corrosion free as it has no electrochemical effect. This makes GFRP a preferred material over steel under harsh environmental service conditions. A detailed review of FRP materials for structures can be found elsewhere [6]. FRP currently gained wide acceptance for retrofitting existing structures (bridges and buildings) because of the ease of installation and high strength to weight ratio. Shear and flexural strengthening for structural concrete using FRP has become a standard practice. Design guidelines for using FRP in concrete structures have been detailed in the ACI-440-2R-08 [7]. However, using FRP to retrofit metal culverts is relatively new and very few investigations have been completed. There are no existing design guidelines to use FRP as a material for retrofitting metal culverts.

On the other hand, FRP pipelines have become a common practice, and many drainage and sewage systems and geothermal pipelines are being replaced using GFRP pipelines because of the corrosion free nature of the material. Moreover, in the areas of harsh environment like sea water piping, industrial waste and when a high purity of water is necessary GFRP has

become widely accepted because of the material ability to serve in harsh environment and to resist corrosion [8]. These systems are mostly buried at a certain prescribed depth in the soil and loads experienced are similar to the culvert systems. Typically, these pipeline systems are designed for a life expectancy of 75 to 100 years.

Given the advantages of GFRP pipelines, this research evaluates the use of a fit-in GFRP profile liner that can be placed inside a corroded metal culvert. It is expected that using GFRP for retrofitting metal culverts when properly designed and implemented can achieve a life of 75 to 100 years. Another advantage is that GFRP profiles can be manufactured in all desired shapes hence using GFRP for metal culvert retrofit can be used for all profiles shown in Figure 1.

# 4. METHODOLOGY

# Materials:

# Corrugated Metal Pipe (CMP):

A 90.0 in. long, 18.0 in. diameter, and 0.064 in. thick CMP was chosen for retrofitting and testing in the laboratory. The choice was based on using a CMP similar to that available in the field and is possible to be tested for its composite capacity in the lab. The CMP was acquired from Contech Engineered Solutions LLC. The CMP section was fabricated using A36 steel and is presented in **Figure 3**.



Figure 3: Corrugated metal pipe

# **Glass Fiber Reinforced Polymer Pipe:**

For the fit-in GFRP profile liner, a filament wound GFRP pipe section with a length of 90.0 in., diameter of 15.0 in. and thickness of 0.35 in. was fabricated and supplied by Sewer Shield Composites LLC to fit the chosen CMP dimension. The GFRP pipe has fibers orientation in  $\pm 45$  degrees along the length of the beam. The GFRP section was fabricated using an amine-based epoxy. The GFRP profiles are presented in **Figure 4**.



Figure 4: Filament wound GFRP pipes for slip-line

# Epoxy grout:

To have the best bond between GFRP and grout material, an amine-based epoxy grout was selected for the retrofit system. An amine based two-component epoxy system supplied by U.S. Composite, Inc., Palm Beach, FL was used along with silica filler to produce the grout material. The primary component of the epoxy system is a low viscous liquid epoxy resin 100% reactive based on Bisphenol-A. The second component is an epoxy-hardener consisting of aliphatic amine. The resin to hardener mix ratio is 2:1 by weight. Silica based aggregate supplied by Transpo Inc., NY, was used as the grout filler. Epoxy and filler material were mixed at 1:1 ratio by volume.

# Material characterization

# **GFRP**

Bidirectional GFRP composites, cut from cylindrical GFRP shell, was tested under direct axial compression and axial tension. For each of the compression and tension tests, samples with two configurations, off-axis and on-axis, were tested. Off-axis samples refer to fibers oriented in 45° with respect to the loading direction and on-axis refer to the fiber orientation

parallel to the loading direction. Details of the fiber orientation and location from which the samples were cut, along with testing protocol, are represented in **Figure 5** and **Figure 6** following ASTM D3039 and ASTM D3518 respectively [9, 10]. The tension tests were conducted on the coupon samples with dimensions 0.5 in wide, 7.0 in long and 0.2 in thick using an MTS® bionix servo hydraulic system with mechanical grips using a cross head displacement rate of 0.08 in/min. The samples and test setup used for tension tests are shown in **Figure 5(b)** and **Figure 5(c)**. The compression tests were conducted using samples with dimensions 3.0 in long, 2.0 in wide and 1.0 in thickness using Forney® compression testing machine with cross head displacement rate of 0.015 in/min. The samples and test setup used for tension tests setup used for compression tests are shown in **Figure 6(b)** and **Figure 6(c)**.



Figure 5: (a) Fiber orientation and samples location; (b) On-axis and off-axis tension samples; (c) experimental setup for tension tests



Figure 6: (a) Fiber orientation and samples location; (b) On-axis and off axis compression samples; (c) experimental setup for compression tests

#### Epoxy grout

The grout material was tested under direct tension and uniaxial compression. Static tension tests were performed using standard dog bone shaped specimens to determine the tensile

strength and tensile Young's modulus of the material based on ASTM D638 as shown in **Figure 7(a)** [11]. A crosshead displacement rate of 0.04 in./min. has been used and the direct tension test setup with contact extensometer is presented in **Figure 7(b)**. The uniaxial compression tests were conducted on 2.0 in. diameter, 4.0 in. long standard specimens based on ASTM C469/C469M [12]. The compression test specimens are presented in **Figure 7(a)**. The compression tests were conducted using 0.04 in./min. crosshead displacement rate and a 120-kip Instron loading frame as shown in **Figure 7(c)**. Strain gauges were used on two of the five specimens to determine the compression Young's modulus of elasticity of the grout material.



Figure 7: (a) Tension and compression test specimens prior to testing; (b) Tension test set-up with a contact extensometer; (c) Compression testing setup.

# **Design of Experimental Set-up**

The loads experienced by culverts are self-weight, soil loads and live loads (traffic, train, aircrafts). The primary objective of the study is to test the composite action of the steel-grout-GFRP culvert. To investigate such an action, a simply supported beam action was chosen for the pipe testing. Since differential settlements, shown in **Figure 8**, in soil is one of the reasons for axial bending in pipeline area [14], the simply supported condition was a reasonable protocol. The pipe section has a span length of 6 ft. which is typically the tributary area under truck wheel load since highway lane width is 12ft as shown in **Figure 9**. Consequently, live load effect was created by a point load application at the mid span location simulating a truck wheel load.



Figure 9: Truck wheel load transferred to the culvert

To accommodate in the laboratory loading frame, a W12x96 section was acquired to ensure negligible deflection of section under loading up to150-kip force. Two semicircular supports were designed and fabricated to have a mechanical hinge used to bolt to the W beam section. These semicircular supports were used to allow bending in the desired direction with one support acting as a hinge and the other support acting as a roller to avoid any axial forces within the section.

# **GFRP** slip-line procedure

To fit in GFRP pipe in the metal corrugated pipe, surface grinding of GFRP pipe (**Figure 10**), using 80 grit sandpaper, was ensured. This maximizes the bond with the epoxy grout GFRP pipe was thoroughly washed using a water jet to remove any debris present on the surface. A wood spacer, as shown in **Figure 11**, was created and bonded to the steel pipe

using thick epoxy. The epoxy could completely seal the gap between the pipe and the wood spacer. The GFRP pipe was then inserted into the corrugated metal pipe. The gap between GFRP pipe and the spacer was then filled with a thick epoxy to completely seal any remaining gaps. **Figure 12** presents the section after GFRP pipe fit inside the corrugate metal pipe.





Smooth glossy surface before grinding



Rough surface after grinding



Figure 10: Surface preparation of GFRP pipe

Figure 11: Wood spacer bonded to the corrugated metal section



Figure 12: Post sliding the GFRP pipe into the corrugated metal pipe using wood spacer

#### **Grouting:**

An amine based two-component epoxy system supplied by U.S. Composite, Palm Beach, FL was used as grout along with a filler material. The primary component is a low viscous liquid epoxy resin 100% reactive based on Bisphenol-A. The second component is an epoxy-hardener consisting of Aliphatic Amine. The resin to hardener mix ratio is 2:1 by weight of the epoxy. T-48 polymer concrete filler supplied by Transpo, Inc., has been used. The epoxy and filler material were mixed at 1:1 ratio by volume. The mixing procedure is outlined in **Figure 13**. A manual grouting pump CG-050M has been acquired from ChemGrout, Inc.



Mix part A and part B of epoxy 3min





Add filler material to the mixed epoxy



Figure 13: Mixing and grouting procedure



Mix for 3 to 5 minutes until a slurry is formed



Using grouting pump, the grout was pumped through one hose until it was expelled from the other hose ensuring grout fill between GFRP and steel pipe. Extra grout was pumped anyway until hose was overflowed thus ensuring complete fill.

# **Testing CMP Retrofitted with GFRP Slip-Liner**

A 3-point bending test was conducted on the CMP section retrofitted with GFRP profile liner. The objective of the test was to determine the level of composite action between the CMP and GFRP, and to determine the ultimate load capacity and modes of failure of the retrofitted CMP. A special test setup was designed with semicircular striped loading and reaction points to allow one hinge support and one roller support. These support conditions aimed to avoid any axial stresses developed in the CMP-GFRP section. A 400-kip Instron loading frame was used to perform the test of the composite section. A cross head displacement rate of 0.012 in./min. was used for testing. The experimental setup is presented in **Figure 14**. Linear Variable Displacement Transducers (LVDTs) were placed at mid span section to measure the deflection of the composite beam and at the end section to observe any debonding and end slip between GFRP, grout material and CMP as shown in **Figure 15**. Strain gauges were used to measure the strain in the GFRP and steel materials. Detailed experimental instrumentation is presented in **Figure 16**. The data was recorded at a sampling frequency of 10 Hz and the test continued for 5 hours and 6 minutes to failure.



Figure 14: Experimental set-up for testing CMP retrofitted with GFRP profile liner under three-point bending



Figure 15: Figure showing the placement of LVDTs to measure midspan deflection and end slip





#### **Computational Methods**

A commercial finite element software ABAQUS was used to model the CMP-GFRP composite section. The model was created using 3D geometry toolbox in ABAQUS. The model consists of steel circular pipe section, grout section and the GFRP pipe section. The steel section was modelled assuming a noncorrugated A36 steel pipe section with a uniform thickness of 0.064in. In reality, the corrugated pipe section behavior is different from noncorrugated section. However, modelling corrugated section may create special problems such as geometrical irregularities and issues with the mesh development for numerical analysis of the system [13]. Therefore, a simplified section has been chosen for the analysis.

For a CMP, the corrugations behave as springs and allow for structural deformation in addition to elasticity of the material itself. It is noted in the literature that an equivalent Young's modulus of the corrugated metal pipe must be considered for the analysis as given by [13]. Also, a lock seam type of connection exists helically along the length of the pipe as shown in **Figure 17**. Under flexure, this lock seam unfolds, and separation takes place. As these joints are typically cold worked, a weakness develops along this joint. A combination of this lock seam separation and corrugation effect must be considered for deciding the Young's modulus of the steel for numerical analysis. The steel section has been defined as an Isotropic, elastic plastic material.



Figure 17: Lock seam joint of the corrugated metal pipe

The epoxy grout material was modelled using 3D geometry toolbox in ABAQUS as a circular pipe section with uniform effective thickness of 1.5in. The grout material was defined as an Isotropic material with concrete damage plasticity model (CDPM). This model was chosen to effectively model different compression and tensile damage behaviors of the epoxy grout based on experimental material characterization.

The four major components in CDPM are Damage evolution, yield criterion, softening law and the flow rule. In order to reflect the non-linearity in concrete, total strain ( $\varepsilon$ ) may be represented in the form of eq 1. where  $\varepsilon^{el}$  is the elastic strain and the  $\varepsilon^{pl}$  plastic strain.

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} \tag{1}$$

A progressive damage capability is provided in CDPM considering a scalar damage variable  $d, 0 \le d \le 1$ , indicating 1 as the total damage and 0 as no damage. This damage is introduced as a uniaxial tension and compression damage variable in the form of softening phenomena with a degradation in material stiffness, shown in eq. 2 and eq. 3.

$$\sigma_t = (1 - d_t) E_0 (\varepsilon_t - \varepsilon_t^{pl})$$
(2)  
$$\sigma_c = (1 - d_c) E_0 (\varepsilon_c - \varepsilon_c^{pl})$$
(3)

 $\sigma_t$  and  $\sigma_c$  are the tensile and compressive stresses respectively,  $d_t$  and  $d_c$  are the tensile and compression damage variables respectively,  $E_0$  is the elastic modulus of the material,  $\varepsilon_t$  and  $\varepsilon_c$  are the strains under tension and compression respectively,  $\varepsilon_t^{pl}$  and  $\varepsilon_c^{pl}$  are the plastic

strains in tension and compression respectively. More detailed explanation on CDPM can be found elsewhere [14, 15].

The GFRP material was modelled using 3D geometry toolbox in ABAQUS as a circular pipe section with a uniform effective thickness of 0.35in. Additionally, Helius progressive failure analysis (PFA), developed based on the multi continuum theory (MCT) technique, considers a representative volume element (RVE) developed to obtain the average stresses in a homogenized composite. Subsequently, the average stresses are decomposed to the stresses of fibers and the matrix discretely in an FEA simulation. This decomposition of stress will help in simulating damage evolution analysis by predicting the failure of fibers and matrix of the composite material.

To determine the constituent stresses and strains from composite stresses and strains, the decomposition of matrix phase and fiber phase is conducted. Considering  $\sigma(x, y, z)$  as the stress field of a homogenized RVE element with a volume "V", stress state of the homogenized composite can be given by,

$$\sigma^{c} = \frac{1}{V} \int_{D} \sigma(x, y, z) dV$$
<sup>(4)</sup>

Similarly, the stress state in fibers and matrix is given by,

$$\sigma^{f} = \frac{1}{V_{f}} \int_{D_{f}} \sigma(x, y, z) dV$$
<sup>(5)</sup>

$$\sigma^m = \frac{1}{V_m} \int_{D_m} \sigma(x, y, z) dV$$
<sup>(6)</sup>

Where,  $V_f$  and  $V_m$  are the volume fractions of fibers and matrix respectively. Combining eqs. 4-6 yields,

$$\sigma^c = V_f \sigma^f + V_m \sigma^m \tag{7}$$

A similar set of expressions for the strain tensor ( $\epsilon$ ) can also be obtained as,

$$\varepsilon^{c} = \frac{1}{V} \int_{D} \varepsilon(x, y, z) dV$$
<sup>(8)</sup>

$$\varepsilon^{f} = \frac{1}{V_{f}} \int_{D_{f}} \varepsilon(x, y, z) dV$$
<sup>(9)</sup>

$$\varepsilon^m = \frac{1}{V_m} \int_{D_m} \varepsilon(x, y, z) dV$$
<sup>(10)</sup>

$$\varepsilon^{c} = V_{f} \varepsilon^{f} + V_{m} \varepsilon^{m}$$
<sup>(11)</sup>

Based on all the above equations, following relation will yield,

$$\sigma^c = \mathcal{C}^c \varepsilon^c \tag{12}$$

$$\sigma^f = \mathcal{C}^f \varepsilon^f \tag{13}$$

$$\sigma^m = \mathcal{C}^m \varepsilon^m \tag{14}$$

Where,  $C^c$ ,  $C^f$  and  $C^m$  represent 6 x 6 stiffness matrices of the homogenized composite, fibers and matrix respectively. Substituting eqs. (12-14) in eq. 7 yields,

$$C^{c}\varepsilon^{c} = V_{f}C^{f}\varepsilon^{f} + V_{m}C^{m}\varepsilon^{m}$$
<sup>(15)</sup>

Using eq. 15 and eq. 11, the following relation is obtained,

$$C^{c}(V_{f}\varepsilon^{f} + V_{m}\varepsilon^{m}) = V_{f}C^{f}\varepsilon^{f} + V_{m}C^{m}\varepsilon^{m}$$

$$(16)$$

By simplification and multiplying both sides of the eq. 16 with  $(V_f(C^c - C^f)^{-1})$ ,

$$\varepsilon^{f} = -\frac{V_{m}}{V_{f}} (C^{c} - C^{f})^{-1} (C^{c} - C^{m})^{-1} \varepsilon^{m}$$
<sup>(17)</sup>

$$A \equiv -\frac{V_m}{V_f} (C^c - C^f)^{-1} (C^c - C^m)^{-1}$$
(18)

Then,

$$\varepsilon^f = A\varepsilon^m \tag{17}$$

Using the above equation, the state of strain in the form of eq. 11,

$$\varepsilon^m = \left(V_m I + V_f A\right)^{-1} \varepsilon^c \tag{18}$$

By using eq. 11 and eq. 18 the state of strain in fibers can be obtained as,

$$\varepsilon^f = \frac{1}{V_f} \left( \varepsilon^c - V_m \varepsilon^m \right) \tag{19}$$

The above set of equations are valid for any type of constitutive behavior and any level of deformation. There are no restrictions on the validity of these equations. The constituent average stress and strain states ( $\sigma^f$ ,  $\sigma^m$ ,  $\varepsilon^f$ ,  $\varepsilon^m$ ) are more relevant to predict the evolution of damage and material failure than the average states of a homogenized composite. This is the fundamental argument of the MCT. Moreover, the damage evolution and failure are primarily dominated by the stress and strain state of the matrix constituent materials rather than the stress and strain in the fiber constituent material or the stress and strain states of the composite itself [16]. A similar statement can be made for fiber constituent material as well. A separate failure criterion for each constituent material is used along with the constituent failure criteria on the constituent average stress state [16]. Moreover, an appropriate stiffness degradation is applied to both fibers and matrix based on stress state and failure. More detailed information on MCT is available elsewhere [16-19].

Semicircular solid 3D supports with a width of 4in, and a diameter of 18in were created as an analytical rigid material. These supports were created to represent the experimental boundary conditions for numerical analysis. Based on the experimental observations, all the three materials were tie constrained assuming perfect bond between GFRP-grout and steel-grout. A mesh size of approximately 2.0in. was used for the model. A C3D8R, an 8-node linear hexahedron, with linear geometric order, was used for the analysis. The appropriate boundary conditions were chosen to represent the experimental condition and provided to the two supports. One support could rotate and translate along longitudinal direction of composite pipe (roller) and the second support was allowed to rotate along the longitudinal direction of the composite pipe (hinged) to avoid any axial forced in the section. The top semicircular

section was loaded under displacement control up to a displacement of 1.2 in. The complete assembly and locations of the boundary conditions are shown in **Figure 18**.



Figure 18: 3D model of steel-grout-GFRP composite pipe

# 5. ANALYSIS AND FINDINGS

# Material characterization

The mechanical properties for GFRP and epoxy grout are presented in **Table. 1**. The mechanical properties examined include Young's modulus of elasticity, tensile strength and modulus for on-axis (0°) and off-axis (45°) GFRP. The stress versus strain behavior of GFRP under direct tension test is presented in **Figure 19(a)**.

| Parameter                  | 0° GFRP             | 45° GFRP          | Grout           |
|----------------------------|---------------------|-------------------|-----------------|
| Tensile strength (psi)     | $54,\!289 \pm 4033$ | $5{,}479\pm651$   | $2,040 \pm 350$ |
| Tensile modulus (ksi)      | $2,794 \pm 107$     | $1{,}088 \pm 184$ | $659 \pm 142$   |
| Compressive strength (psi) | $15240 \pm 1200$    | $10720\pm200$     | $8392\pm421$    |
| Compressive Modulus (ksi)  | NA                  | NA                | $1,590 \pm 112$ |

| Table 1: Mechanical Properti | es of GFRP and Epoxy Grout |
|------------------------------|----------------------------|
|------------------------------|----------------------------|

The stress versus strain behavior of the polymer grout material under axial compressive and tensile stresses are presented in **Figure 19(b)**. The polymer grout behavior represents a



typical behavior exhibited by polymer concrete under compression and tension stresses [20].

Figure 19: Stress strain behavior of; (a) GFRP under tension; (b) Epoxy grout

#### **CMP-GFRP** composite pipe

The load versus deflection behavior of the CMP-GFRP composite section is presented in Figure 20(a). The CMP-GFRP composite pipe was tested under three-point bending configuration until the final deflection reached 3.52 in. This was the maximum deflection possible for the test configuration, so the test was terminated at that time. The composite section was able to observe higher deflection than the maximum reported here. The load versus deflection behavior exhibited a linear elastic behavior up to a load of 57.6 kip. At this force the strain data indicated a strain reading of 0.002 in./in. for steel. After this point, the behavior was nonlinear until the peak load of 75 kip was reached. The load started to drop after reaching the peak load. The post peak behavior exhibited significant deformability until the test was stopped at maximum deflection of 3.52 in. while the CMP-GFRP system retained 62% of the peak load at 46.6 kip. The toughness of the CMP-GFRP composite section has been calculated as the area under the load-deflection curve. The calculated toughness at the peak load was 28.1 kip-in and at the end of the test was 211.6 kip-in. This indicates that 653% higher toughness was observed after the peak load. The overall ductile behavior of the CMP retrofitted GFRP system can be attributed to the very ductile material behavior of the individual materials steel, polymer grout, off-axis GFRP material, and the superior bond between both GFRP and steel to the polymer grout material.

The composite section capacity was predicted using the transformed section properties considering steel yielding as failure. The capacity was predicted based on the linear elastic behavior of the three materials, i.e., GFRP, steel (CMP) and epoxy grout from the experimental results above. eqs (20), (21) and (22) presented below were used to predict the capacity. The moment of inertia of the three materials can be additive due to the concentric nature of the three sections being CMP, grout and GFRP.

$$I_{t} = (I_{steel} * n_{steel}) + (I_{Grout} * n_{grout}) + (I_{gfrp})$$

$$M = \frac{f_{y} * I_{t}}{y_{s} * n_{s}}$$
(20)
(21)

$$P = \frac{M * 4}{L}$$

$$P = \frac{M * 4}{L}$$

$$\int_{0}^{0} \frac{1}{100} \int_{0}^{0} \frac{1}{100} \int_{0}^{0$$

Figure 20: (a) Load versus deflection behavior of steel-GFRP composite beam; (b) Strain profiles in GFRP at different load levels with corresponding loads in (a) at mid span; (c) Strain profiles in GFRP at different load levels with corresponding loads in (a) at 15.0 in. from the support.

The predicted load capacity of the CMP-grout-GFRP composite section, based on above equations and yielding of steel, was 56.4 kip, which is in close agreement with the experimental load observed at initiation of nonlinearity of 57.6 kip. The strain distributions in GFRP, at the midspan section and at 15.0 in. from the support location, are presented in **Figure 20(b)** and **Figure 20(c)** respectively. Because of the corrugations in CMP, the strain readings in steel were not always very accurate. As the strain distribution is always linear, the strains in steel can be predicted. The measured strain (in./in.) in GFRP midspan location in compression at various load levels, i.e., 20 kip, 40 kip, 60 kip, 75 kip were -0.00023, -0.00035, -0.00063 and -0.00113 respectively. The strain readings (in./in.) on the tension side were 0.00025, 0.000688, 0.00179 and 0.00230. These strain readings indicate that a full composite action existed between steel, polymer grout and GFRP until the peak load. If all the materials in the section exhibit an isotropic behavior, the neutral axis must exist at the

(22)

center. However, the non-symmetric neutral axis is mainly because of orthotropic behavior of GFRP. Figure 21(b) shows the neutral axis shifting down as the load progressed to the peak load. It is also important to note that the thickness of the grout material (1.5 in.) is higher compared to that of the steel (0.064 in.) and GFRP (0.35 in.). Therefore, the grout material will have a higher moment of inertia compared to both steel and GFRP. The results from Table 1 also show that tensile modulus of epoxy grout is much lower compared with compression modulus of the grout material. This justifies the downward shift of the neutral axis. The strain readings from **Figure 21(c)** indicate that GFRP experienced strains at 15.0 in. location from the support.



Figure 21: Failure modes identified on the load-deflection curve of the CMP retrofitted using GFRP profile liner and the corresponding loads. Figure insets show the behavior at different loads. Inset (a) shows separation of steel at point (ii) of the load deflection curve. Inset (b) shows the GFRP failure due to off-axis tension at point (iii) of the load-deflection curve

The modes of failure of the CMP-GFRP section to the corresponding peak loads were identified and are shown in **Figure 21**. First, the point at which the steel yielded is shown. Second, failure mode at the peak load is shown. Failure at the peak load occurred because of separation of the CMP joint located exactly at the mid span section of the beam as shown in **Figure 21(a)**. For CMP-GFRP composite section, compression existed on top of the beam and maximum tension existed below the neutral axis at the bottom farthest location. At the peak load, the strains in GFRP reached -0.00113 in./in. in compression and 0.00230 in./in. in tension, much lower than the failure strains of GFRP. Extrapolated strain in grout material in compression was -0.00150 in./in. and in tension was 0.00301 in./in. indicating the grout material reached its peak strain and may have failed. An inference can be made that failure of grout and separation of joint occurred at the peak load. Beyond this point, the strains in GFRP increased significantly. At point (iii), shown in **Figure 21(b)**, GFRP on the tension side started to fail as the strain in GFRP reached 0.036 in./in., which is very close to the

typical off-axis failure strain in GFRP. Nevertheless, no signs of failure in compression were observed at this point of loading.



Figure 22: GFRP failure at the end of the test

**Figure 22** shows the complete failure of GFRP at the end of the test. The separation of corrugated steel pipe at the end of the test is presented in **Figure 23**. The deflected beam at the end of the test is presented in **Figure 24**. The above results indicate that a full composite action existed between GFRP, polymer grout and steel until the peak load was reached.

Moreover, the first failure was because of separation of the corrugated steel pipe joint with about 115% of the failure load taking place in the GFRP.



Figure 23: Corrugated steel pipe joint complete separation at the end of the test



Figure 24: Deflected retrofitted CMP using GFRP profile liner at the end of the test with total deflection of 3.52 in

The above results prove that the fit-in GFRP profile liner was able to retrofit the CMP and a full composite action was developed. The proposed method for sliding the liner and filling the gap with a polymer grout worked very well. A limitation of the above study is that it has been performed on a non-corroded CMP. The significance of CMP corrosion is its bond with the polymer grout and the impact of corrosion on the composite action of the retrofitted CMP. Finally, relatively high cost of GFRP compared with other techniques for retrofitting can be justified by its significant structural capacity compared with all other retrofitting systems. Furthermore, the use of filament winding technology will allow using this technique with metal culverts with any dimension and cross-section and is not limited to circular sections.

# Finite Element modeling results

A commercial finite element software ABAQUS was used to model the CMP-GFRP composite section. The system was developed making use of the 3D geometry toolbox in ABAQUS. The model consists of steel circular pipe section, grout section and the GFRP pipe section. All the three materials were tie constrained by assuming perfect bond between GFRP-grout and steel-grout. The corrugation of the steel pipe has been neglected for the Finite Element Analysis (FEA) model. A mesh size of approximately 2.0 in was used for the model. A C3D8R, an 8-node linear hexahedron, with linear geometric order was used for the analysis. The FEA model was loaded using a ramped static displacement protocol up to a deflection of 1.2in. The FEA model developed for the study is presented in **Figure 25**.



Figure 25: CMP-GFRP composite pipe numerical model showing (Units: psi)

The corrugated metal pipe was made using A36 steel. Steel was modeled as elastic-plastic material with a Young's modulus of elasticity of 29,000 ksi and Poisson's ratio of 0.3 to start the modelling. The behavior exhibited an extremely stiff behavior. Literature indicated when the CMP is subjected to bending, the material behavior is governed by the corrugation and the lock seam joint. Therefore, a reasonable modulus of elasticity which may represent the realistic behavior i.e. a Young's modulus of elasticity 8000 ksi and a yield strength of 33000 psi were used as the material parameters. Based on experimental observations, the separation of the joint initiated when the nonlinearity in experimental load vs displacement initiated. The author believes, as the separation of lock seam increased and no noticeable increase in the tensile force contribution for the leaver arm towards flexural capacity was contributed. Therefore, with a plastic strain of 0.4 and an ultimate strength of 35000 psi elastic-Plastic behavior was defined. As part of the ongoing work, a joint tension test is necessary to understand the lock seam joint behavior to completely validate the model with experimental work.

The grout material has been characterized as an isotropic material and concrete damage plasticity (CDP) has been used to model the damage as a function of degradation in stiffness for hardening and softening behavior of the material. Moreover, a Young's modulus of 403 ksi with a Poisson's ratio of 0.22 assuming a linear elastic behavior to peak load was used. Stress-strain of the grout material extracted from the material characterization stage were used in the FE model. The model parameters developed to represent the behavior and fit the CDPM are presented in **Table 2.** A semicircular ring was used to represent the supports and

loading head with boundary conditions similar to those used in the testing. The model is shown in **Figure 18**. The GFRP pipe has been modelled using composite layup tool box in ABAQUS. The composite layup has been carried out in 60 layers and a local discrete coordinate system has been assigned. The composite layup is presented in **Figure 26** with a repeated layup of 90°, +45°, -45°, +45°, -45°. The material properties for the GFRP pipe section were defined based on the orthotropic elastic properties based on results from **Table 3**. The parameters for 0° direction were used from the experimental investigation and 45° results were used to determine the shear modulus and shear strength. The 90° properties were used from the literature which used GFRP with similar matrix and epoxy type [21].

| σ <sub>t</sub> | ε <sub>ck</sub> | dt   | $\sigma_c$ | ε <sub>in</sub> | d <sub>c</sub> |
|----------------|-----------------|------|------------|-----------------|----------------|
| psi            | in/in           | -    | psi        | in/in           | -              |
| 2100           | 0.0000          | 0.00 | 2500       | 0.0000          | 0.00           |
| 1500           | 0.0017          | 0.29 | 3000       | 0.0009          | 0.00           |
| 1300           | 0.0024          | 0.38 | 3500       | 0.0030          | 0.00           |
| 900            | 0.0045          | 0.57 | 4000       | 0.0045          | 0.00           |
| 300            | 0.0069          | 0.86 | 3921       | 0.0106          | 0.00           |
| 250            | 0.0089          | 0.88 |            |                 |                |
| 200            | 0.0109          | 0.90 |            |                 |                |

Table 2: CDPM parameters for grout material

Table 3: GFRP laminate properties

| E <sub>11</sub> | E <sub>22</sub> | G <sub>12</sub> | $+S_{11}$ | -S <sub>11</sub> | $+S_{22}$ | -S <sub>22</sub> | V12  |
|-----------------|-----------------|-----------------|-----------|------------------|-----------|------------------|------|
| ksi             | ksi             | ksi             | psi       | psi              | psi       | psi              |      |
| 2794            | 625             | 1088            | 54289     | 15240            | 2040      | 6816             | 0.16 |



Figure 26: Composite layup of GFRP filament wound pipe

The load versus displacement behavior comparing experimental to the numerical analysis is presented in **Figure 27**. The behavior from numerical analysis agrees well with the experimental observations. This model is limited to the mesh size 2.0in only. Further investigations are necessary by conducting the mesh sensitivity analysis to verify the model. Stress strain behavior of the steel element is presented in **Figure 28**. The behavior agrees reasonably well with the input parameters of elastic-plastic behavior of steel. Stress strain behavior of the grout tension element is presented in **Figure 29**. The behavior agrees reasonably well with the input tensile parameters of CDPM as shown in **Figure 29**. The stress vs strain behavior of GFRP tension element is presented in **Figure 30**. With the stress strain behavior, a drop can be observed at 1500 psi. As some of the laminate layers are in 90° direction and corresponding tensile strength is 1500 psi and the rest of the fibers in 45° are carrying the load. This can be represented by the change in stiffness after drop.



Figure 27: Load vs displacement curve comparing numerical solution with the experimental



Figure 28: Stress vs strain behavior of steel element in tension from the model



Figure 29: Idealized grout stress versus strain given as input for the model (Input) and grout behavior from the model (FEA)



Figure 30: Stress vs strain behavior GFRP tension element from the model

The global behavior of the model represents an identical behavior to the experimental behavior. An inference can be made that the drop-in load capacity after reaching 82 kip can be attributed to the grout tension failure and steel not being able to take any more force beyond max force and deform significantly to maintain the stress at 40000 psi. However, as GFRP complete failure was not observed and carried the stress. Therefore, the load carrying capacity further increased after the drop. Stress versus time step behavior is presented in **Figure 32.** A clear observation can be made that when grout failure was achieved, a steep climb in the stress can be observed with steel. At this point of the experiment a drop-in force associated with significant joint separation was observed. Grout failure has increased the stress significant for steel and this caused a sudden separation of steel. This inference can be

justified, by conducting a lock seam joint tension test. The lock seam joint test can validate the input parameters of steel used to calibrate and fit the experimental load displacement curve. This justifies the hypothesis of grout failure followed by joint separation caused the initial failure at peak load.



Figure 31: stress vs time step behavior of steel and grout element in tension from the model

#### Life cycle cost analysis of proposed retrofitting technique

Life cycle cost (LCC) analysis is a technique to evaluate the comparative cost of a system over the entire service life or a specific period involving economic factors to individual phases for a system with time as a function [22]. These phases have significant influence on the total LCC of a system. In the proposed study, LCC analysis will be performed on the use of GFRP for retrofit of the culverts. An environmental life cycle costing scheme with detailed phases has been proposed by Sarja et. al., 2003 [23]. The phases presented in **Figure 32** are much more generalized for any type of structural system.



Figure 32: Different phases of LCCA [29]

Typically, total life cycle cost can be divided into two components; agency costs and social costs [24]. Agency costs can be related to the direct costs associated with the three phases described in **Figure 32**. Social costs refer to the indirect costs due to inconvenience caused to people. For this current study, it can be referred to user delay cost, vehicle operating costs and environmental costs. Environmental costs can be considered by conducting a Life-cycle assessment.

# Objective of Life cycle cost analysis:

Currently, three main materials, steel, PVC and HDPE are used for retrofitting the existing corroded culverts. It is important to compare the LCC for these three materials with GFRP as a material retrofitting. In New Mexico, steel culverts are corroding within 3 years of installation in certain regions. A study reported that HDPE pipes have caused several types of failures and service life is significantly lower compared to the design life of the culvert. PVC is significantly brittle in cold climates. The proposed technology in this study, with a high specific strength of GFRP, shows great potential to eliminate problems caused by both PVC and HDPE systems and overcome the corrosion problem with steel. To estimate the appropriate LCC for each material, the parameters presented in **Figure 33** will be considered.



Figure 33: Phases to be considered for LCC analysis in propose study [22]

As part of the LCCA, a survey methodology is proposed with target population including but not limited to NMDOT officials of different districts in New Mexico. A simple approach based on the tools of generalization of the questionnaire and a deductive scale development is used by providing a generalized set of options as explained by Hinikin, 1998 [25]. Five tasks will be included in the survey process. They are,

- 1. Preparation of a questionnaire
- 2. Identifying NMDOT officials to exchange questionnaire
- 3. Exchanging conversations with NMDOT officials and collect answers
- 4. Documentation and analysis of the obtained answers
- 5. Scientific and statistical quantification of survey outcomes

Questionnaire for NMDOT officials of different districts:

1. What is the typical service life of a CMP in the corresponding district?

District name\_\_\_\_\_

 $\circ$  1-10 years

- 10-20 years
- 20-30 years
- Others\_\_\_\_\_
- 2. What are the different materials presently used for slip lining a corroded CMP culvert?
  - Poly vinyl chloride (PVC)
  - High density polyethylene (HDPE)
  - o Steel
  - Others\_\_\_\_\_
- 3. After retrofitting corroded CMP culvert in the corresponding district, what is the

typical service life?

- $\circ$  1-10 years
- 10-20 years
- 20-30 years
- Others\_\_\_\_\_
- 4. What are the issues with currently used materials for slip lining?
  - Material \_\_\_\_\_
  - Specific issue \_\_\_\_\_
- 5. Was there a CMP culvert failure in your district? Can you provide details of the failure? (describe briefly)
- 6. What is the frequency of CMP culvert inspection over its life span?
  - $\circ$  3 months

6 months
1 year
Others

The above questions have been identified to understand the concerns with specific materials and their service life before and after retrofit.

#### Present Value Analysis

This method for cost analysis has been outlined elsewhere [29]. A structure will incur financial cost when the design and planning phase is started and will end with its end of service life. The cost process from monetary means can be acquired from different phases outlined in **Figure 26**. Using the current value discounting method, the LCC final costs can be calculated using eq. 23,24:

$$E_{tot}(t_d) = E(0) + \sum [N(t) * E(t)] - E_r(t)$$
(23)

Where,  $E_{tot}$  is the design life cycle monetary cost as a present value,  $t_d$  is the design life, E(0) is the construction cost, N(t) is the coefficient for calculation of the current value of the cost at the time t, E(t) is the cost to be borne at the time t after construction and  $E_r(t)$  residual value at time t.

$$N(t) = 1/(1+i)^n$$
(24)

Where, *i* is the rate of interest and *n* is the time in years from the date of discounting.

The total cost calculated here may increase with an increased design life. For this value to be comparable between different techniques, the cost must be normalized by the design life.

#### 6. CONCLUSIONS

A new retrofitting technique using fit-in GFRP profile liner for CMPs used in culverts has been developed and tested. A fit-in GFRP liner was able to retrofit a CMP by sliding the GFRP liner and filling the gap with a polymer grout. The GFRP liner was surface prepared and slid inside the CMP. An epoxy grout was used to fill the gap. The CMP-epoxy grout-GFRP section was tested under static load to failure in three-point bending. The CMP-GFRP composite section had a maximum load capacity of 75 kips. The primary mode of failure identified for the composite section is the separation of corrugated steel joint and grout failure in tension at 75 kip and then rupture of the GFRP. GFRP failure only took place at the mid-span of the beam. For the rest of the beam the GFRP was intact. Finite element analysis showed that the CMP-epoxy grout-GFRP developed a full composite action until the peak load was observed. The load versus deflection behavior indicates a ductile composite section. A finite element model to simulate the behavior was developed and showed good agreement with the experimental observation. The model is being used for the design of the retrofitting system. GFRPs corrosion resistance and high specific strength to weight ratio can improve service life expectancy of in-service CMP culverts to additional 75 years. Field implementation of the GFRP retrofitting technology is being conducted through a new project funded by New Mexico Department of Transportation. Field implementation of a 20 ft, 24" diameter corroded metal pipe is being design and is planned to take place at the end of 2019 and start of 2020.

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