Journal of Scientific & Industrial Research
Vol. 82, July 2023, pp. 767-775
DOI: 10.56042/jsir.v82i07.2493

# Trenchless Mechanized Inspection and Retrofitting Strategy for Buried Sewerage Systems

Ravindra Singh Bisht[1]*, Dinesh Kumar[1], Naman Garg[1], Vikesh Kumar[1], Siddharth Singh[1], Sameer[1], Soraj Kumar Panigrahi[1] & Ajay Chourasia[2]

[1]Construction Automation and Robotics Group, [2]Structural Engineering Group, CSIR- Central Building Research Institute, Roorkee 247 667, Uttarakhand, India

*Received 16 March 2022; revised 19 May 2023; accepted 08 June 2023*

The conventional retrofitting methods of buried sewer pipes require heavy machinery, intensive manpower, and a longer time for rehabilitation. Such methods may also damage the nearby infrastructures and landscapes. The present study explores an integrated trenchless solution for damage identification and mechanized retrofitting of domestic buried sewerage pipelines of diameter ranging from 75 to 300 mm. A front-mounted camera of the retrofitting system assesses the damage inside the sewer pipes. The retrofitting of the damaged part of buried pipe is achieved by impregnation of Glass Fiber Reinforced Polymer (GFRP) composite sheet with 100:16 epoxy and hardener ratio. The wrapping of the GFRP sheets on damaged part is done by inflation and deflation technique with a cylindrical rubber bladder connected by a flexible shaft. The retrofitted sewer pipe can be resumed after 3–4 hours of applying the impregnated GFRP composite with above retrofitting strategy.

**Keywords:** Damage detection, Fiber-reinforced polymer, In-pipe retrofitting, Mechanized system, Rubber bladder

## Introduction

The sewerage system could fail and damage at any time due to tree root intrusion, cracks, channeling, or misaligned pipeline connections, and land settlement due to earthquakes and other external loading conditions. Extreme symptoms of sewerage system deterioration include foundation issues such as cracks in the foundation slab, foundation settlement, and in some cases, formation of deep sinkholes. Severe failures in the sewerage system may also lead to flooding damage in building structures, environmental hazards such as degradation of groundwater quality, and public health hazards by epidemic diseases due to clogged sewerage wastewater. The wastewater from damaged pipe may find its way elsewhere apart from the mapped-out drainage system.[1] It is extremely difficult to identify the damage location and quantification of the buried sewerage system manually.[2] Mechanized retrofitting of the buried sewer pipeline is the key requirement to avoid major failures.

Direct human inspection and retrofitting is impractical for sewerage pipelines because of buried sewerage system networks, unsafe and unhealthy environment, low visibility, and small diameter pipe size.[3] Sewer pipes are generally made of clay, concrete and Polyvinyl Chloride (PVC) materials. The conventional retrofitting method of sewer lines requires heavy machinery, intensive manpower, and a longer time period for pipeline rehabilitation. Making open trenches and repairing the pipe line will create health hazards and pollution. The excavation and replacement of deteriorated pipelines as method of sewer rehabilitation along the path-way may disturb the road traffic.

Open trenching is time consuming and may also damage the nearby infrastructures and landscape. Also, about 80% of the total sewerage systems worldwide meet the non-man-entry classification for less than 800 mm diameters.[4] Sewer defects can be categorized into three categories viz., structural, construction and maintenance type.[5] Structural defects are due to cracks (longitudinal, circumferential and spiral types), joint flaws (angular, offset, separation and fracture), deformation and collapse. Construction defects are another type of irregularity due to aging and improper fixing of the sewer pipes. Maintenance defects are due to tree root intrusion, water infiltration, and obstacles due to deposits and running the service pipe without periodic inspection and maintenance.[6,7]

*Author for Correspondence
E-mail: rsbisht@cbri.res.in

Hence trenchless technology is best option for sewage retrofitting in urban areas.[8] Old methods of sewer retrofitting like insertion of a pipe inside the sewer reduces the area of cross-section of the pipe considerably. To allow pieces of the new pipe to be inserted into the host pipe, an open cut is required. It is also tough to install fresh pipe in the bends of the pipe for repair. To overcome the above-mentioned problems, Fiber Reinforced Polymer (FRP) is used as suggested in other studies.[9] A reinforcing composite fabric, consisting of carbon or glass fibers, is soaked with epoxy resin in the field and pasted to the internal surface of the pipe. The notion of reinforcing structures by external bonding FRP, i.e. the wet lay-up technique, established two decades ago for strengthening concrete specimen.[10] Due to corrosion resistance property, lightweight and high-pressure capacity, FRP composites are best suitable.[11] The technique known as wet layup system is used to retrofit large size of damaged pipes manually. The fiber sheet is coated with a thick resin and epoxy mixture, which is wrapped around a packer and inserted into the repair location. The packer is inflated and maintained in place until the resin is hardened.[12]

The installation of flexible polymeric liners with thermosetting resin within existing pipes is known as Cured in Place Pipe (CIPP) lining technology. When compared to standard pipeline retrofit methods, CIPP offers a cost-effective and environmentally favorable option for pipeline rehabilitation.[13,14] The trenchless renewal technique (CIPP) for small, medium, and large diameter sewer pipes has respective construction costs 57%, 63%, and 18% lower than open-cut pipeline replacement.[14] Few other literatures have also been reported using the inflatable rubber bladder to wrap the FRP and epoxy inside the damaged sewer pipeline.[15,16]

Various in-pipe inspection/cleaning robotic systems have been explored in detail by various researchers.[17–22] The in-pipe robots used different locomotion configurations viz., wheel, multi-legged, crawler, inchworm/serpentine, screw, multibody and aerial types. Apart from the discussed locomotion techniques, additional mechanisms such as wall-pressing, propulsive, scissors and stretching mechanisms have also been explored in the development of in-pipe inspection/cleaning robots.[18,20,22] The wheel-drive in-pipe inspection/cleaning robots achieve movement through rotation of various active and passive wheels/joints. They employed geared motor-drive mechanisms for turning and maneuverability.[18,21,22] Similarly, other types of in-pipe inspection/cleaning robots work on the principle of actuating their respective mechanisms.

It is seen from the literature that mechanized and robotic systems have been developed and explored for separate inspection and retrofitting tasks of buried pipes, but integrated inspection and retrofitting system has not been explored yet. The integrated approach will drastically save inspection and repair time of the buried sewerage pipes. Another key issue needs to be addressed is the adaptation to retrofitting to various sizes, curvatures and materials of the sewer pipe.

These issues have been addressed in the present study by adopting inflated rubber bladder mounted on a flexible wheeled locomotion-based mechanized system for in-pipe retrofitting. The selected retrofitted materials can be adopted for a wide variety of pipe materials. The present work explores a complete solution for integrated inspection and sewage retrofitting using a High-Definition (HD) camera and mechanized retrofitting system to address trenchless rehabilitation of sewer pipeline. The wheel locomotion with an inflatable rubber bladder mounted through a flexible body makes it unique and easily adaptable to various pipe sizes and curvatures. The mechanized retrofitting system has been successfully tested for various sewer pipe materials (PVC and concrete) with diameters ranging from 75 mm to 300 mm over a length of 5–10 meters. The depth of repair site is extendable (up to 20 meters) and it is case-dependent. The damage identification and retrofitting solution for domestic buried sewerage pipelines have been validated in the field.

## Materials and Methods

### Materials

Considering the desirable features of fiber composites wrap for strengthening of sewage pipes, different fiber composites and epoxy resins were selected to strengthen the buried sewer pipe. Fiber composites were broadly categorized into: (i) Glass Fibers Composites (GFRP), (ii) Carbon Fibers Composites (CFRP), and (iii) Basalt Fibers Composites (BFRP). The detailed properties of fiber composites from the literature are compared in Table 1.[(23–26)]

According to cost and strength, the GFRP and BFRP were most suited and opted as suggested in the literature. Epoxy resins are generally used as a

Table 1 — Different types of fiber composites and their properties

| Properties | GFRP | | | | | CFRP | | | BFRP |
|---|---|---|---|---|---|---|---|---|---|
| | E-Glass with Kevlar | E-Glass without Kevlar | | E-Glass without Kevlar | | | | | Continuous |
| Ultimate tensile strength (MPa) | 575 | 575 | 575 | 521 | 575 | 1062 | 1172 | 986 | 1360–1585 |
| Tensile modulus (GPa) | 26.1 | 26.1 | 26.1 | 26.1 | 26.1 | 102 | 102 | 95.8 | 93.1–110 |
| Ultimate elongation (%) | 2.2 | 2.2 | 2.2 | 2.0 | 2.2 | 1.05 | 1.0 | 1.00 | 3.1 |
| Density ($g/cm^3$) | 2.55 | 2.55 | 2.6 | 2.55 | 2.55 | 1.81 | 1.8 | 1.74 | 2.63–2.8 |
| Weight GSM ($g/m^2$) | 915 | 915 | 925 | 505 | 505 | 224 | 315 | 644 | — |
| Laminate thickness (mm) | 1.3 | 1.3 | 1.3 | 0.635 | 0.64 | 0.18 | 0.33 | 1.00 | 0.8 |

Table 2 — Different types of epoxy resins and their properties

| Properties | Epoxy Resin (LY-556) | Hardener (HY-951) | Epoxy Resin (GY -250) | Hardener (K -16) |
|---|---|---|---|---|
| Appearance | Clear | Clear | Clear | Clear |
| Flash point (°C) | Below 200 | 110 | ≥ 200 | — |
| Viscosity at 25°C (mPa.s) | 10000–12000 | — | 10,000-12,000 | — |
| Density at 25°C ($g/cm^3$) | 1.15–1.20 | — | 1.17 | — |
| Mixing ratio | 100 | 10 | 100 | 16 |
| Curing life at 20°C (hours) | 14–24 | | 3–4 | |
| Pot life at 20°C (minutes) | 30–60 | | 40–50 | |

polymer matrix material for binding the composites with the host pipe for extra strengthening. Epoxy resin can also be effectively used for filling minor cracks. A suitable epoxy resin selection is crucial in retrofitting buried sewerage pipes. The details of various epoxy resins (epoxy and hardener) are mentioned in Table 2.[25,27,28]

The performance evaluation of different types of epoxy resins have been done for the retrofitting purpose. Commercially available LY-556/HY-951 and GY250/K-16 epoxy resins have been used in the retrofitting experiments. However, the best results are obtained for commercially available epoxy GY-250 and hardener K-16 in terms of fast curing time and settlement compared to resin (LY-556/HY-951). For the present study, the GFRP sheet of 925 GSM and selected epoxy resign (GY250/K-16) are mixed in the ratio of 100:16 that have been used to retrofit the damaged part of the sewer pipe. The surface morphology analysis is done using concrete samples impregnated with GFRP and epoxy using Field Emission-Scanning Electron Microscopy (FE-SEM). The analysis is useful for proper mix-ratio and effect of coating on a concrete surface.

The surface morphology results are shown in Fig. 1. From Fig. 1(a), the bare/untreated and rough concrete surface can be seen, whereas, Fig. 1(b) shows the smooth and defect-free concrete surface after application of epoxy and hardener coating on the concrete surface as desired for post repairing scenario of retrofitted sewer pipe. From the FE-SEM analysis, Fig. 1(c) shows the fiber thickness of 20 $\mu m$ GFRP composite. Smooth finishing can also be seen for

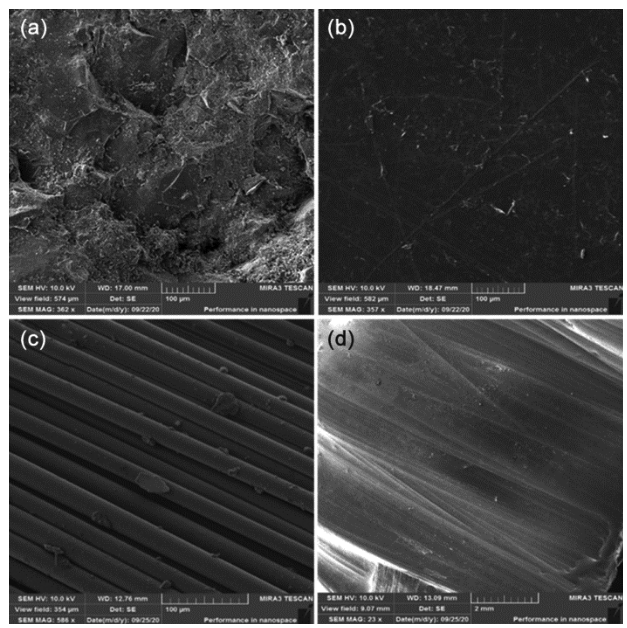


Fig. 1 — FE-SEM analysis of samples treated by GFRP

epoxy resin impregnated GFRP composite on a concrete surface in Fig. 1(d), which infers that the coating can be used for filling minor cracks. Furthermore, the FRP with epoxy resin can be used for extra strengthening for repairing of damaged sewer pipe apart from filling the minor cracks.[29]

**Strength Tests**

After selecting retrofitting material (GFRP, GY-250 epoxy and K-16 hardener), the standard cube specimens ($150 \times 150 \times 150$ $mm^3$) have been prepared for strength testing using Universal Testing Machine (UTM) of capacity 100 ton. A minimum three untreated and treated samples were prepared for strength test. The sand, cement and admixture ingredients were used to prepare the testing samples in Fig. 2(a) and 2(b). Uniaxial compression loading was used to measure the compressive strength of the samples. The average compressive strength was found to be 38 MPa for untreated samples, whereas the treated samples show the average value of 46 MPa. Overall, the GFRP treated samples exhibit 14–22% increment in compressive

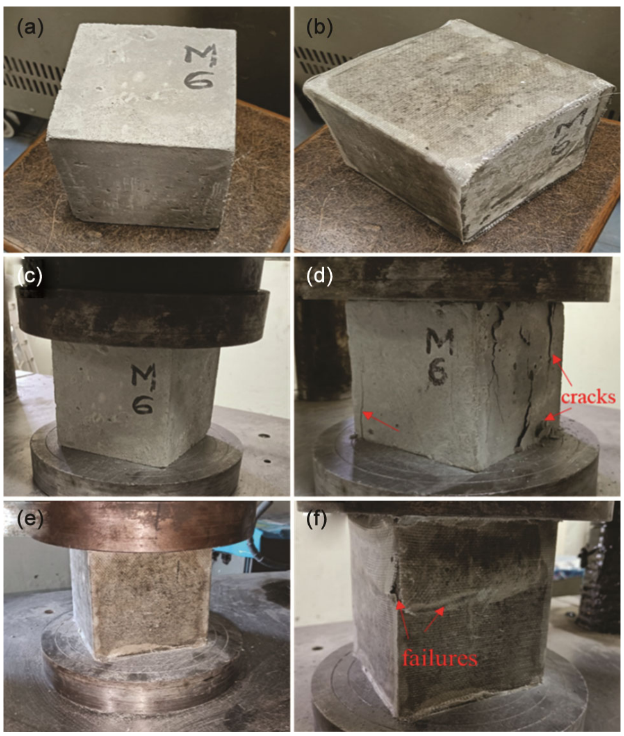


Fig. 2 — Strength testing: (a) Untreated sample (b) FRP treated sample, (c)-(d) untreated sample before and after failure, (e)-(f) FRP treated sample before and after failure due to loading in UTM

strength. It was also observed from the experiments as in Fig. 2(c–f) that the treated and untreated test samples show the cracks and failure of the wrapped FRP strip due to loading beyond its compressive strength. A study has reported overall 20–40% increment in flexural strength of FRP/epoxy treated damaged pipe samples.[23] A four-point test-set up configuration is rsequired for the flexural testing of the pipe/beam elements and is mentioned elsewhere.[30]

The working trials and manual wrapping of GFRP with epoxy and hardener mix are shown in Fig. 3(a–d). The damaged sewer pipe is shown in Fig 3(a). The host surface should be cleaned before retrofitting the damaged pipe. After cleaning, Fig. 3(b) depicts application of epoxy coating done manually on inner side of sewer pipe, whereas Fig. 3(c) shows FRP wrapping and manual pressing around the pipe for better adhesion.

The impregnated GFRP with epoxy/hardener mix is wrapped manually to evaluate the performance of the mix-ratio and GFRP as shown in Fig. 3(d). The manual retrofitting of epoxy/hardener mix impregnated on GFRP shows good adhesion on the bottom side of the sewer pipe. However, from the manual trials, the upper side of the pipe portion showed difficulty in adhesion with frequent delamination and air voids as shown in Fig. 3(e). The improper paste of FRP wrap can be seen during manual retrofitting of the host pipe and uniform pressure is required to stick the FRP wrap over the host pipe surface at least for its pot life. This can be considered a major drawback of manual retrofitting, which was rectified in the present study on inflation and deflation-based retrofitting technique as discussed in the next section.

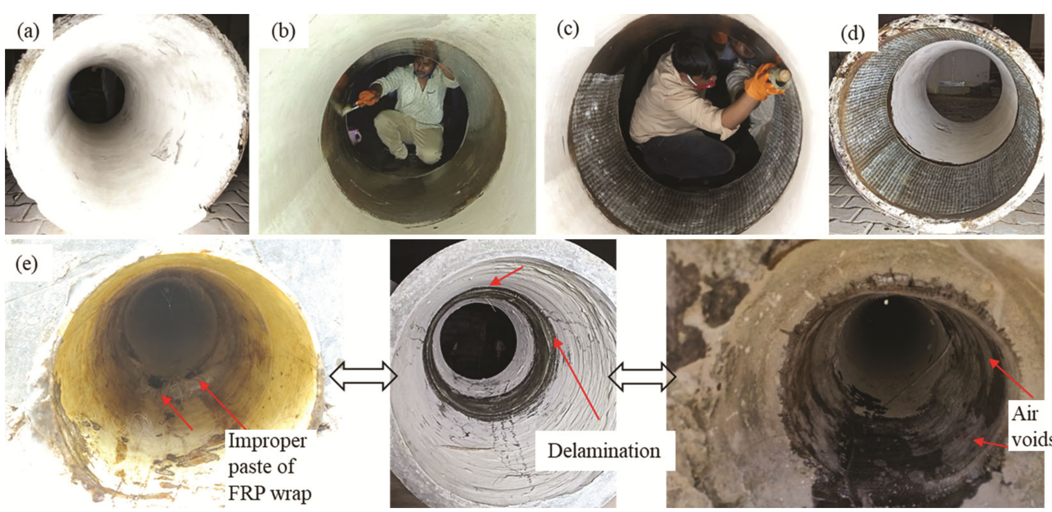


Fig. 3 — Manual FRP retrofitting strategies of sewer pipes

### Methodology

Although FRP composites and epoxy resins are best suited for retrofitting, the main challenges encountered are identifying the location of damage and applying composites to the identified location of the sewer pipe. A complete solution is explored for sewage retrofitting using a high-definition camera and mechanized retrofitting system to address this issue. The mechanized retrofitting system is based on an integrated rubber bladder system with a manually operated air flow control unit.

The impregnated GFRP is applied to the desired location inside the sewer pipe by inflation and deflation technique of rubber bladder. This method is more convenient than the previously developed open trench pipe repair techniques. The coated GFRP with epoxy and hardener mix is wrapped on partially inflated cylindrical rubber bladder. The whole system is inserted inside the sewer pipe and inflated up to 35 psi until the rubber bladder come in contact with the inner sewer pipe surface and uniformly pressurizes the GFRP sheet to stick with the damaged part. After the pot life of applied epoxy resin (40–50 min.), the bladder is deflated and the mechanized system is retracted from the sewer line. The service of repaired sewer pipe can be resumed after complete curing of epoxy resin with FRP (3–4 hours). The whole design concept of inflation and deflation of rubber bladder technique can be seen from Fig. 4–5. The rubber bladder placement inside the sewer pipe through a manhole is represented in Fig. 4, whereas, a closer look on the system with deflated and inflated shape of bladder for pasting the FRP sheet on the host pipe is represented in Fig. 5.

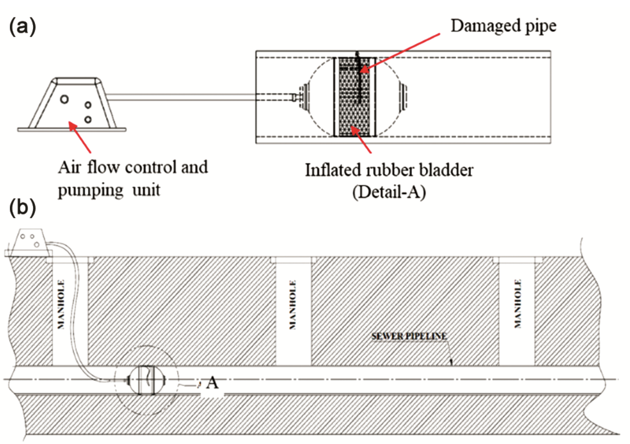


Fig. 4 — Mechanized retrofitting procedure of FRP using inflated rubber bladder technique

## Mechanized Retrofitting System

### Design and Prototype

The mechanized system for damage identification and retrofitting is shown in Fig. 6. The mechanized platform consists of specially designed wheels to move along a curved surface inside the concrete sewer pipe. The front part has Ingress Protection (IP-65) rating video camera system for damage location and identification as shown in Fig. 6(a), while different parts are specified in Fig. 6(b).

The design parameters of the retrofitting system are shown in Fig. 6 and summarized in Table 3. Further,

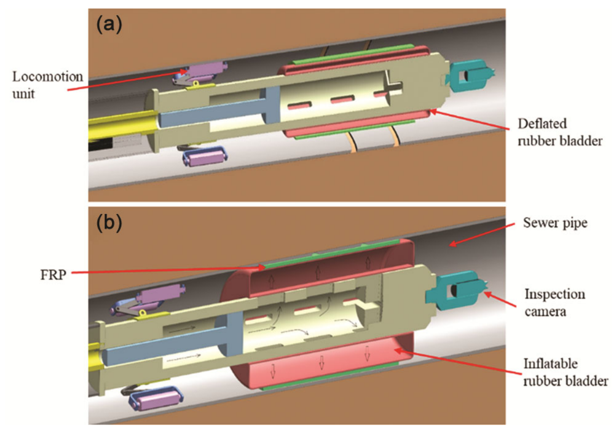


Fig. 5 — Inflated rubber bladder technique with coated epoxy/hardener on GFRP

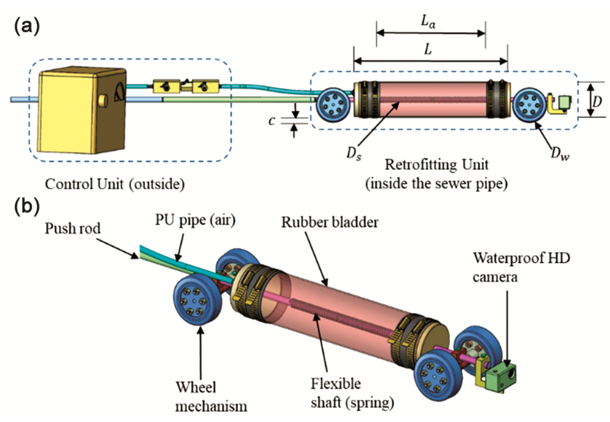


Fig. 6 — Assembly design and parameters of the retrofitting system

Table 3 — Specifications of the mechanized retrofitting system

| Design parameters | Values (mm) |
|---|---|
| Total length ($L$) | 550 |
| Active length ($L_a$) | 400 |
| Bladder deflated diameter ($D$) | 75 |
| Bladder inflated diameter | 300 |
| Body flexible shaft diameter ($D_s$) | 16 |
| Wheel diameter ($D_w$) | 70 |
| PU pipe diameter | 10 |
| Push rod diameter | 20 |

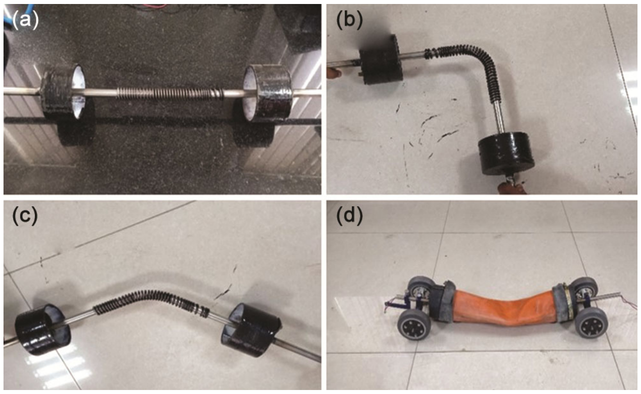


Fig. 7 — Bendable flexible shaft incorporation in retrofit mechanism for better adaptability

the parameters shown in Table 3 can be varied according the length and deflated diameter of the used rubber bladder, accordingly the wheel size can be decided to provide ground clearance for in-pipe locomotion. The ground clearance ($c$) also depends on the mounting of the wheel shafts. Generally, it can be taken as the difference in wheel and deflated rubber bladder radius.

Two supporting wheel mechanism units are connected by a spring based flexible shaft that has been provided for retrofitting of pipe bends as shown in Fig. 7. This also support the system when the length changes during the inflation of rubber bladder. A complete kit with different components used for retrofitting is shown in Fig. 8.

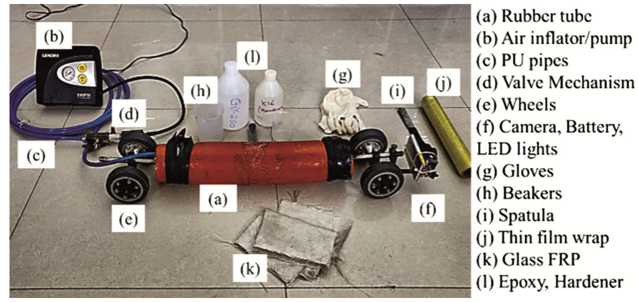


Fig. 8 — The integrated mechanized retrofitting system

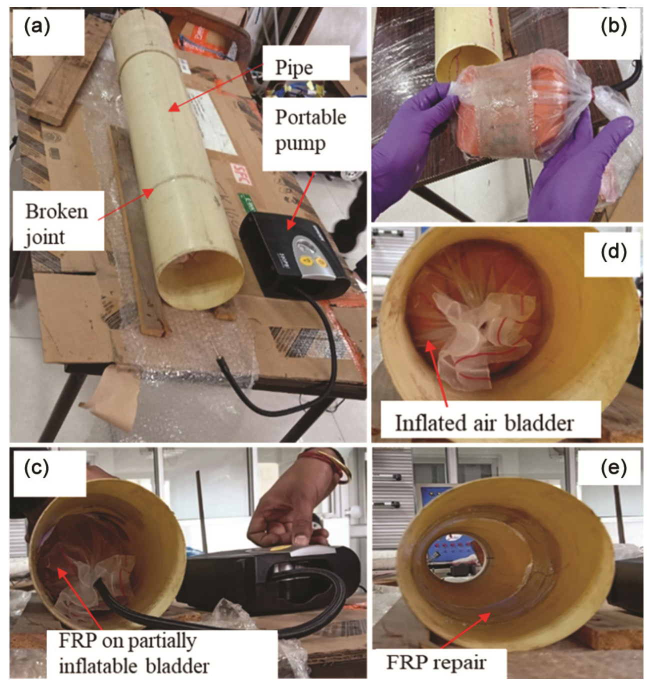


Fig. 9 — Laboratory set-up for FRP repair of internal pipe

## Results and Discussion

### Concept Validation

For major cracks and spalling cases, wrapping of GFRP is preferred. The laboratory set-up shown in Fig. 9(a–e) represents the concept validation of wrapping GFRP sheet on inner pipe surface of a damaged PVC pipe. The inflation and deflation of rubber bladder by portable air pump using mechanized system is adopted for retrofitting trials. The inflated shape of the rubber bladder provides a uniform normal pressure to apply FRP wrap to the host pipe.

### Field Trial and Implementation

The initial trials were started with different sizes of rubber bladder units where concept of small crack repair by epoxy resin was implemented. Hit and trial experiments were also conducted for selection of best ratio of epoxy resin and hardener mix to get minimum curing time and maximum strength. Pipes with small cracks were only treated with resin hardener mix. The epoxy resin has filled the minor cracks and holes and after completion of curing time, the resin- hardener mix gets settled hard into it. The testing for leaks has been done by flowing water through the pipe and no leaks have been seen except for the big cracks. Trials have been done on multiple pipes of different diameter size to check the limitation of the bladder unit. During field trials, the sewer pipe retrofitting required sequential procedures viz., damage location and retrofitting for successful implementation.

The installation of WiFi HD camera enables the user to inspect the pipeline for probable damage and retrofit in a single operation. The utility of the front mounted HD camera for damage location can be seen from Fig. 10(a–f). The front mounted Light-Emitting Diode (LED) lights provide sufficient illumination during dark in-pipe locomotion.

For retrofitting of the damaged pipe surface, the GFRP sheet was impregnated with the specified

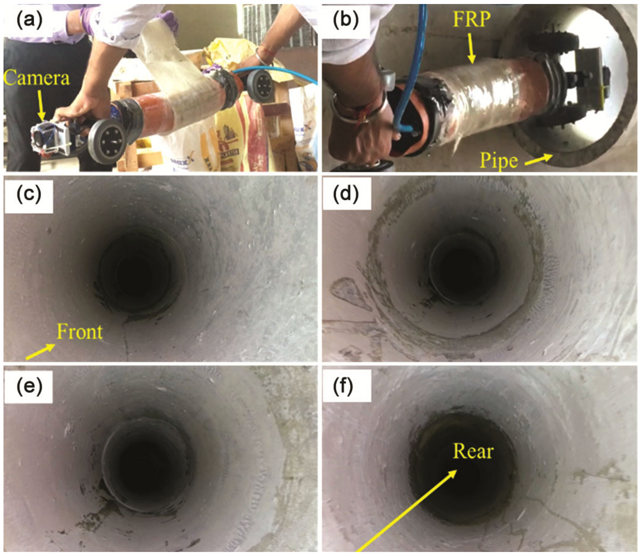


Fig. 10 — Utility of the front mounted HD camera for damage location

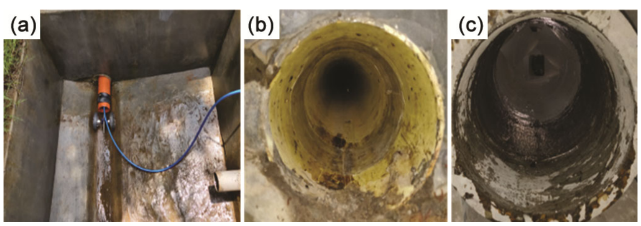


Fig. 11 — Field implementation and retrofitting of sewer pipe line

epoxy resin and hardener in a defined ratio (100:16). Then the prepared GFRP sheet was wrapped around the partially inflated rubber bladder, which is cylindrical in shape. The wheel locomotion system with GFRP wrapped bladder was introduced into the host pipe section in the next step. The bladder was gradually inflated using compressed air to uniformly press the impregnated GFRP against the host pipe's internal wall. The excess epoxy-resin penetrated into the pipe's cracks and voids, and the remaining one created a tight-fit, permanent bond against the host pipe. After completion of pot life, the bladder system was deflated and pulled back.

The complete integrated mechanized system has been developed for field trials and implementation in various concrete as well as PVC sewer pipes, as shown in Fig. 11. As evident from Fig. 11(b), the proper retrofitting of 250 mm PVC sewer pipe has been successfully implemented. Similarly, Fig. 11 (c) shows proper adhesion of GFRP on the concrete pipe surface with 250 mm diameter. The setting/curing time of epoxy and hardener mix is 3 hours which has to be given for proper setting of GFRP impregnated epoxy on cracked sewer surface.

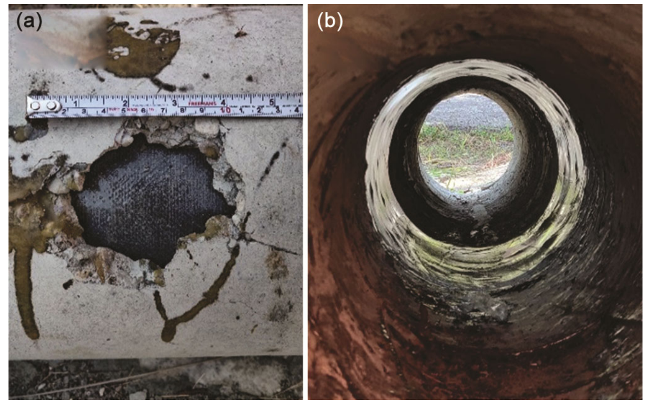


Fig. 12 — Retrofitting trials of damaged portion of the sewer pipe

From the field trials, Fig. 12(a) shows the size of crack repaired using GFRP sheet and Fig. 12(b) shows inside view of the repaired sewer pipe. The results obtained are robust and high-quality retrofitting by the developed mechanized retrofitting system compared to the manual operations. The sewer can be resumed after the complete curing (3 hours) of the retrofitted portion of the pipe. The passive wheel of locomotion unit can be easily pushed to the desired fault location of the pipe, and if it is required, a push rod may be additionally used. The proposed method is also best suited for local damage repair of in-pipe to save extensive retrofitting materials. The mechanized retrofitting process is easy to use, simple and quick process compared to the other trenchless techniques viz., wet lay-up, CIPP, and grout-in-place pipe methods. These trenchless techniques take slightly longer time for sewer pipe rehabilitation as they are useful for repairing the entire existing pipeline.

As evident from the several trials, the epoxy coating and GFRP with epoxy retrofitting shows different strategies for damaged sewer pipe rehabilitation. First, the epoxy coating can be used only to waterproof the hairline minor (crack size ≤ 1 mm) cracked pipe. In contrast, the second approach of using epoxy with GFRP is used to attain strength as well as waterproofing of the damaged pipe. The second approach can be best suited for pipes with major damage (size: 75 mm to 300 mm), especially when large cracks are visible and measurable.

## Conclusions

In this study, integrated inspection and retrofitting strategies have been implemented using developed mechanized retrofitting system for buried sewerage pipes. The commercially available epoxy resin and hardener were mixed in 100:16 ratio and applied on GFRP which showed proper adhesion on concrete and PVC sewer pipe. The repair of small cracks, defects, and leakage tests were performed by the epoxy and hardener mix. Large cracks/holes were repaired by GFRP impregnated with epoxy hardener mixture by using the proposed retrofitting technique. The whole process of damage identification, assessment, and in-pipe retrofitting may take in between 3–4 hours, which is much less than the conventional process. The developed trenchless approach may be considered cost-effective and time-saving compared to open-trench and other trenchless repair techniques especially used for repairing the entire pipelines. The future works are noted as below:

- Motorized wheels can be further integrated with the proposed system for its effective insertion and retraction from the sewer pipe.
- Automatic air flow-control and pressure monitoring system should be added to improve its performance.
- Strength tests such as: split tensile strength/hoop/flexural strength of damage pipe with different materials can be further investigated for strength comparisons.

## Acknowledgments

The authors are grateful to the Director, CSIR-Central Building Research Institute, Roorkee, for the encouragement during the research work and permitting to publish the paper. This work is part of CSIR funded project: MLP-052002. Authors would also like to thanks Dr. L. P. Singh and Dr. Srinivasrao Naik B. for providing the material characterization facility and Dr. S. R. Karade for providing the UTM testing facility.

## References

1 Dolowitz D P, Bell S & Keeley M, Retrofitting urban drainage infrastructure: green or grey?, *Urban Water J*, **15(1)** (2018) 83–91.

2 Kirkham R, Kearney P D, Rogers K J & Mashford J, PIRAT - a system for quantitative sewer pipe assessment, *Int J Rob Res*, **19(11)** (2000) 1033–1053.

3 Guo W, Soibelman L & Garrett Jr J H, Automated defect detection for sewer pipeline inspection and condition assessment, *Autom Constr*, **18(5)** (2009) 587–596.

4 Truong-Thinh N, Ngoc-Phuong N & Phuoc-Tho T, A study of pipe-cleaning and inspection robot, in *IEEE Int Conf on Rob and Biomimetics* (IEEE) 2011, 2593–2598.

5 Moradi, S, Zayed T & Golkhoo F, Review on computer aided sewer pipeline defect detection and condition assessment, *Infrastructures*, **4(1)** (2019) 10.

6 Cheng J C & Wang M, Automated detection of sewer pipe defects in closed-circuit television images using deep learning techniques, *Autom Constr*, **95** (2018) 155–171.

7 Yin X, Bouferguene A & Al-Hussein M, Data-Driven Sewer Pipe Data Random Generation and Validation, *J Constr Eng Manage*, **146(12)** (2020) 04020131.

8 Gupta BS, Chandrasekaran S & Ibrahim S, A survey of sewer rehabilitation in Malaysia: application of trenchless technologies, *Urban Water J*, (**4**) (2001) 309–315.

9 Ehsani M, Latest advances in pipeline renovation with fiber reinforced polymer (FRP), in *Water Distribution Syst Anal*, (2010) 200–208.

10 Ehsani M R & Saadatmanesh H, Fiber composite plates for strengthening bridge beams, *Compos Struct*, **15(4)** (1990) 343–355.

11 Lim K S, Azraai S N, Noor N M & Yahaya N, An overview of corroded pipe repair techniques using composite materials, *Int J Mater Metall Eng*, **10(1)** (2015) 19–25.

12 Ehsani M, Superlaminate: the next generation of carbon FRP products for repair of pipelines, *In Pipelines 2010: Climbing New Peaks to Infrastruct Reliab: Renew, Rehab, and Reinvest*, (2010) 1280–1289.

13 Zhong Z, Wang S, Zhao M, Du X & Li L, Performance of ductile iron push-on joints rehabilitated with CIPP liner under repetitive and seismic loadings, *Soil Dyn Earthquake Eng*, **115** (2018) 776–786.

14 Kaushal V, Najafi M, Serajiantehrani R, Malek Mohammadi M, & Shirkhanloo S, Construction cost comparison between trenchless cured-in-place pipe (CIPP) renewal and open-cut replacement for sanitary sewer applications, in *Pipelines*, (2022) 171–177.

15 Perez C, Trenchless technologies for the rehabilitation of sewers: Case study of the Patapsco interceptors, Baltimore, *J Public Works Infrastruct*, **2(4)** (2010).

16 Carroll J B, Kozman D P & Marc-Aurele C, Assessment and Application of Trenchless Technologies for the Rehabilitation of Sewer Laterals, in *Pipelines* (Reston, VA) 2020, 256–262.

17 Montero R, Victores JG, Martinez S, Jardón A & Balaguer C, Past, present and future of robotic tunnel inspection, *Autom Constr*, **59** (2015), 99–112.

18 Mills G H, Jackson A E & Richardson R C, Advances in the inspection of unpiggable pipelines, *Robotics*, **6(4)** (2017) 36.

19 Zhao W, Zhang L & Kim J, Design and analysis of independently adjustable large in-pipe robot for long-distance pipeline, *Appl Sci*, **10(10)** (2020) 3637.

20 Yang W & Zhang W, A worm-inspired robot flexibly steering on horizontal and vertical surfaces, *Appl Sci*, **9(10)** (2019) 2168.

21 Ren T, Zhang Y, L Y, Chen Y & Liu Q, Driving mechanisms, motion, and mechanics of screw drive in-pipe robots: A review, *Appl Sci*, **9(12)** (2019) 2514.

22 Kakogawa A & Ma S, Design of a multilink-articulated wheeled pipeline inspection robot using only passive elastic joints, *Adv Rob*, **32(1)** (2018) 37–50.

23 Jayasuriya S, Chegeni B & Das S, Use of BFRP wrap for rehabilitation of pipeline in bending with various corrosion depths, *J Pipeline Syst Eng Pract*, **11(1)** (2020) 04019038.

24 Sivasaravanan S, Sangeetha M, Prakash S, Reddy T D & Rahul D P, Experimental investigation of composite material laminated with Aloe vera fiber in different composite resin, *Mater Today Proc*, **16** (2019) 832–837.

25 Szewczak A, Influence of epoxy glue modification on the adhesion of CFRP tapes to concrete surface, *Materials*, **14(21)** (2021) 6339.

26 Farooq M & Banthia N, Strain-hardening fiber reinforced polymer concrete with a low carbon footprint, *Constr Build*, **314** (2022) 125705.

27 Singh K P, Singh A, Kumar N & Tripathi D N, Morphological features, dielectric and thermal properties of epoxy–copper cobaltite nanocomposites: preparation and characterization, *Bull Mater Sci*, **43** (2020) 1–10.

28 Arputhabalan J, Karunamoorthy L & Palanikumar K, Experimental investigation on the mechanical properties of aluminium sandwiched sisal/kenaf/aloevera/jute/flax natural fibre-reinforced epoxy LY556/GY250 composites, *Polym Polym Compos*, **29(9)** (2021) 1495–1504.

29 Alabtah F G, Mahdi E & Eliyan F F, The use of fiber reinforced polymeric composites in pipelines: A review, *Compos Struct*, **276** (2021) 114595.

30 Mohamed H M & Masmoudi R, Flexural strength and behavior of steel and FRP-reinforced concrete-filled FRP tube beams, *Eng Struct*, **32(11)** (2010) 3789–3800.