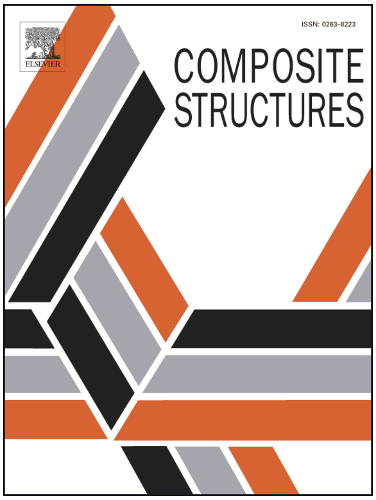

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An overview of burst, buckling, durability and corrosion analysis of lightweight FRP composite pipes and their applicability

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Abstract

The main aim of this review article was to address the performance of filament wound fibre reinforced polymer (FRP) composite pipes and their critical properties, such as burst, buckling, durability and corrosion. The importance of process parameters concerning merits and demerits of the manufacturing methods was discussed for the better-quality performance. Burst analysis revealed that the winding angle of ±55° was observed to be optimum with minimum failure mechanisms, such as matrix cracking, whitening, leakage and fracture. The reduction of buckling effect was reported in case of lower hoop stress value in the hoop to axial stress ratio against axial, compression and torsion. A significant improvement in energy absorption was observed in the hybrid composite pipes with the effect of thermal treatment. However, the varying winding angle in FRP pipe fabrication was reported as an influencing factor affecting all the aforementioned properties. Almost 90% of the reviewed studies was done using E-glass/epoxy materials for the composite pipe production. By overcoming associated limitations, such as replacing synthetic materials, designing new material combinations and cost-benefit analysis, the production cost of the lightweight FRP composite pipes can be decreased for the real-time applications.

Keywords: Filament winding; composite tubes; impact response; burst analysis; corrosion; winding angle; numerical simulations.

Contents

Abbreviations, symbols or nomenclatures and their meanings

Abbreviations	Meaning
FRP	Fibre reinforced polymer
FWM	Filament winding method
RCW	Rotary centrifugal winding
V_f	Volume fraction
RIM	Resin infusion moulding
HCl	Hydrochloric acid
H_2SO_4	Sulfuric acid
CPVC	Chlorinated polyvinyl chloride
HPDE	High density polyethylene
PP	Polypropylene
PVC	Polyvinyl chloride
FEP	Fluorinated ethylene propylene
PVDF	Polyvinylidene fluoride
ECTFE	Ethylene chlorotrifluoroethylene
CAGR	Compound annual growth rate
FGH	Functionally graded hybrid

UV	Ultraviolet
BFR	Basalt fibre reinforcement
GFRP	Glass fibre reinforced polymer
CNT	Carbon nanotube
MWCNT	Multi-wall carbon nanotube
GRP	Glass-reinforced plastic
AE	Acoustic emission
PE	Polyethene
MDPE	Medium density polyethene pipe
FEM	Finite element method
CFRP	Carbon fibre reinforced polymer

1. Introduction

Nowadays, the fibre reinforced polymer (FRP) composite pipes attract more attention in oil and gas industries, due to the advantages of corrosion resistance and structural flexibility. The rapid growth of composite materials expands their feather almost to all the engineering applications. This is due to their unique advantage of lower weight to higher specific strength [1,2]. The FRP composite materials are extensively used in lightweight structural components as a result of their versatile behaviour of reinforcements and polymer matrices [3,4]. Also, the FRPs in the form of composite pipes are becoming more and more attractive mainly due to their higher moduli, weight savings and less installation costs [5,6]. Hence, these pipes are preferred for many engineering applications in aerospace, automotive, marine, agriculture and wind turbine sectors [7-9]. On the other hand, properties such as high specific strength, good fatigue strength and excellent corrosion resistance are the essential requirements for the transportation of hot mediums [10-12]. In these circumstances, it is important to exploit more knowledge about the design and performance of FRP composite pipes towards achieving enhanced properties. The concurrent engineering on material, design and fabrication needs to be well addressed to achieve better quality [13]. Accordingly, a better understanding of the fabrication processes and its state-of-art technology are of great and prime importance.

Generally, FRP composite pipes have been produced using two distinct production methods namely filament winding method (FWM) and rotary centrifugal winding (RCW). To best of our knowledge, any long fibres in form of roving, chopped strand mats and any thermoset polymers can be used as source materials in FWM [14,15]. Furthermore, the advantages such as production of larger pipes, hollow pipes, fibre arrangement, high mechanical performance, minimum production time attract the manufacturers towards this process [16-18]. There are several factors such as material combination, geometric features and manufacturing process that are involved in the prediction of the mechanical properties of composite pipes [19,20]. However, controlling the parameters, such as winding angle, stacking sequence, the pretension of fibre, amount of resin on impregnation of fibre can lead to achievement of better properties of FRP pipes. In this regard, a study was carried out for the enhancement of mechanical properties of any composite pipes through an analytical approach, with minimum wall thickness [21]. The factors such as optimal fibre, matrix, volume fraction (V_f) and winding angle θ were considered for the analysis. The results showed that the optimal level of volume fraction of $40\% < 60\%$ and winding angle $\pm 44.5° < \theta < \pm 52.5°$ exhibited better performance of the FRP composite pipers used in oil and gas industries. Though, many studies have been reported on FWM [22-24], yet, there is still need to address some of the recent developments. In this route, an innovative fabrication processes called coreless and assembled windings have been successfully experimented for a few case studies in the field of construction building and materials [25]. From the FWM advancement point of view, the use of modern technology, such as computational tools and adaptive winding frame can effectively overcome the constrained of precise changing of winding angle in FWM. In this perspective, a recent work on the state-of-the-art of FWM concerning design and fabrication of composites for a structural performance was reported [26]. Furthermore, the suitability of filament wound composite pipes with cylindrical, torus section and non-geodesics for various applications was elaborated.

Secondly, a centrifugal force concept was applied to the development of FRP composite pipes. RCW was largely used for metal matrix composites rather than polymer matrix composites [27]. It is too extensively for the thermoplastic polymer as well as the reinforcements in the form of short fibres and fabrics. The RCW method is mainly used to produce hollow and composite tubular to the larger extent. However, there are many factors such as melting temperature, centrifugal speed, impregnation pressure, followability of melted polymer and curing timing that are significantly influencing the materials performance [28]. A detailed study for some of the important parameters of RCW has been discussed [29]. Similarly, the effect on the fibre weight has been studied, with respect to some parameters such as centrifugal force, roll pressure and impregnation pressure. Consequently, a method called thermoplastic endless centrifugal process has been introduced to avoid the aforementioned drawbacks. In which, they have discussed the control of parameters through macro and microscopic analysis and observed out suitable criteria for the reinforcement materials with better properties. The advantages and disadvantages of two manufacturing methods with information on their suitability for an industrial application are presented in Table 1.

Recently, CoroTech US-based company developed a new technique, called resin infusion moulding (RIM) for the fabrication of FRP pipe [30]. It possesses the main advantage of an environmentally friendly approach. Moreover, through this approach, a high-volume fraction of fibre was achieved for a wide range of thermoset resin systems. Nevertheless, there was no much work in the production of composite pipe using RIM technique. Future work with the successful design of controlling parameters through computer automation can make this method more flexible and user-friendly. Several researchers have reviewed the performance of FRP composite pipes concerning mechanical and impact properties [16,31,32]. However, there is no review articles on burst, buckling, corrosion and durability performance of FRP composite pipes, based on the extensive literature search. Moreover, all these properties are very important for the fast-growing industries, such as oil and gas, petrochemical and offshore industries.

Hence, all these industries are largely looking for the applicability of new FRP pipes with a different combination of ingredients. Hence, this review article mainly focuses on the demand of sustainable FRP composite pipes and the primary required properties required by the concerned industries. Accordingly, the effect of burst analysis on commercial filament wound pipes with varying pressure conditions for different applications of loading has been considered. Furthermore, the buckling, corrosion and durability behaviours of various FRP pipes in different environmental conditions have also been considered. The failure mechanisms associated with the FRP composite pipes was described within the properties considered and scope of this comprehensive study.

2. The significance of FRP composite pipes in industry scenario

It is a well-known fact that the demand of FRP composite pipes is increasing regarding production and also a wide range of applications since the 1950s, as shown in Fig.1 [33,34]. The affordable performance and long-term cost benefits of FRP composite pipes attract more consumers. In general, FRP composite pipes can exhibit high strength to low weight ratio, excellent corrosion resistance, low coefficient of friction, low thermal conductivity and better dimensional stability and more importantly lower installation and maintenance cost [35-37]. Hence, any good combination of FRP composite pipe can be a suitable replacement for other traditional materials, such as carbon steel, stainless steel, rubber lined carbon steel, high nickel alloys and lined steel materials [38-40].

The other important aspect is the design criteria of the piping system which has to be effectively done with the suitable choice of material combinations. Because of this, the factors such as corrosion tolerance, pressure range, vacuum level, maximum temperature, abrasion behaviour, flammable nature and electrical conductivity must be considered for the design of the piping system to transport oil, gas and chemical medium [36,41,42]. Also, the common factors related to the physical and mechanical behaviours of piping systems: ultimate strength of pipes, type of supports, correction factors for thermal expansion, among others, are also important. Furthermore, the noise factors such as burial loads, wind, snow and seismic considerations also need to be taken into account before the material design [33]. Often, FRP composite pipes are exposed to impact damage during installation and occasionally also during service. However, the installation of these polymer composite pipes is a bit easy and take less time for the erection. The comparison of installation costs in various aspects; between steel pipe and the composite pipe is presented in Table 2.

Generally, the main function of polymers in FRP composite pipe is to provide binding affinity for the fibre and to offer better corrosion and chemical resistance during service. The FRP laminate with a large amount of matrix content can provide better corrosion resistance when exposed to the practical condition [43-46]. Due to this advantage, nowadays polymers can also be used as corrosion barrier/liner material at the inner surface of the pipe [47]. However, the type of polymer and thickness of this corrosion barrier/liner depends upon the real-time situation. This high corrosion resistance characteristic of polymers is essentially needed for the production of pipes and fittings, tanks, process vessels, columns, scrubbers, air and fume handling equipment – duct, stacks, plenums – chlorine headers, electrolytic cells, hoods, covers, structural beams, grating, stairs, platforms, anode boxes, static mixers, strainers, electro winning cells, penstocks, and linings [48]. Similarly, the enhanced chemical resistance behaviour can help the FRP composite pipes to transport hydrochloric acid (HCl), sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), chlorine gas wet, chlorine gas dry, chlorine dioxide, sodium hydroxide and sodium hypochlorite as well as solvent extraction solutions [49]. Also, properties such as viscosity, cost, strength, fabrication flexibility, chemical resistance and conductivity are also considered when selecting polymers for the production of FRP pipes [50].

As a recent development, the transportation industries (aeronautical and automobile engineering) also utilising the benefits of FRP composite pipes to some extent [51]. In the aerospace application, the FRP composites are used to fabricate less weight and damage resistant composite fuel pipe. It enables to achieve the benefit of weight savings and cost savings, using reducing the number of hardware currently used. In addition to impact and fatigue strength, the electrical conductivity of the fuel pipe can be enhanced by the addition of suitable conductive filler in the polymer matrix. It can provide resistance to lightning strike propagation and to satisfy the need of conducting static electric field obtained from the flowing liquid. FRP composite pipe can also use conductive fibres, co-mingled with the mainstream glass fibres, to exhibit electrical conductivity of the material to ground the system and avoid accumulation of static charge. Moreover, FRP composite pressure vessels are being used for storing of gases/fluid in aerospace [52]. Besides, the automobile industries also exploit the usage of the FRP composite pipes for the production of transmission shafts or drive shafts [53].

FRP composite pipes are also implemented in power plant industries and performed successfully even after 22 years of service. In 1970, three projects started in USA with FRP composite pipes; one at Florida with 16.3 ft (5 m) diameter pipe for discharging hot water from the plant outlet. The other two projects were implemented in New York State with the dimensions of 10 ft and 12 ft (3 m and 3.6 m, respectively) pipe penstocks, to power stations [54]. Similarly, the other leading manufacturing company Amitech in Brazil produced FRP composite pipe with the length of 1128 m and varying diameter from 1.9 m to 2.2 m for small hydroelectric plant project at Brazilian city of Jaciara, Mato Grosso [55]. Furthermore, Amitech of Brazil that fabricated FRP composite pipes for construction industries earned 40% of the increase in turn over in a year. The FRP tubes for the pontoons of the dock was designed with end caps and foam filling. It can maintain dock remains ‘unsinkable’ in case of any unexpected situations, such as pontoons got punctured [56].

Currently, FRP composite pipe industries are using both thermoset and thermoplastic polymers to the maximum possible extent [57-59]. Accordingly, thermoset polymers such as epoxy, polyester, vinyl ester, phenolic, and furan thermosets were used significantly for pipe productions [60]. Similarly, the thermoplastic polymers including chlorinated polyvinyl chloride (CPVC), high density polyethylene (HPDE), polypropylene (PP), polyvinyl chloride (PVC), fluorinated ethylene propylene (FEP Teflon), polyvinylidene fluoride (PVDF Kynar) and ethylene chloro tri fluoroethylene (ECTFE Halar) are used for various piping applications [61]. The other important segment of FRP production is the selection of suitable reinforcement [62-64]. Meanwhile, this reinforcing element only can provide required strength and stiffness to the material. There are several synthetic fibres glass [65], carbon [66], kevlar [67], basalt [68] and various natural fibres such as sisal [69], banana [70], hemp [71], flax [72], kenaf [73] and coir [74], among others, have been used as successful reinforcement elements in various polymer systems. However, the effective suitability of the polymer matrix and reinforcement used in composite pipe fabrication depends upon many factors. Detailed information about the suitability and characteristics of the polymer matrix and reinforcement concerning various applications is presented in Table 3. To a large extent in two circumstances, the FRP pipes can work; firstly, in underground and the other is in a horizontal arrangement. Hence, buckling effect, bending strength, impact resistance and modulus of composites need to be considered before application.

Similarly, the stability of the composite pipes is also other important parameter to be studied to understand the deformation and stiffness changes of pipes in various loading conditions [75]. Normally, the stability of the composite pipes depends upon various factors, such as time, temperature, boundary and environmental conditions. Sometimes, the dynamic instability can occur at different situations, such as in suspension bridges, airplanes, fluid conveying pipes, rotating shafts, impacted bodies and machine elements subjected to excessive vibratory motions. Generally, the dynamic instability occurs in elastic bodies when the applied forces are non-conservative. Admittedly, composite pipes are flexible in nature with high stiffness subjected to various loading systems. However, the serviceability of composite pipes is mainly affected by the condition of working mediums/loadings. Accordingly, the following factors needs to be considered during the design of composite pipes to retain the sustainable stability under static and dynamic buckling [76,77].

(1) Proper dimension with significant safety factors (laminate thickness, ply orientation).

(2) Material and pipe weakness (material selection, design of composite construction, geometric section of pipes).

(3) Initial deformations and geometric imperfections.

(4) Installation faults (improper support conditions, load distribution).

(5) Fixed points and change of directions.

(6) Time dependent working conditions (Creep, time, load, temperature).

(7) Intermediate repairs.

(8) External interventions.

The overall buckling (buckling and post buckling) behaviour of CFRP was investigated and fitted with the standard model [78]. From the analysis, the abrupt changes in the elastic curve were noticed during the transformation from buckling to post buckling process. Furthermore, the CFRP tubes exhibited brittle failure after reaching the critical load at the post buckling region. Similarly, the stability of the composite thin wall tube was analysed using numerical method with the effects of various parameters, such as fibre orientation angle, volume fraction of fibre, composite lay-up, size of fibre, structural damping coefficient, mass fluid ratio and elastic boundary conditions [79]. During the experimental process, the cantilever boundary condition was assumed with spring support at free end. Analysis revealed that the volume fraction and fibre size have stabilising effects on the dynamic behaviour of the system. Moreover, it was reported that the stability of the composite pipes depended on the spring constant value of the spring.

Reports of FRP pipe manufacturing industries stated that the use of FRP composites have contributed to the definite growth recorded by many sectors, and expanding their applications in a wide variety. The applicability of FRP composite pipes in various industrial sectors is shown in Fig.2. From the marketing data, it was observed that the FRP pipes would be identified more for transporting hot and chemical mediums effectively rather than weight saving. FRP piping industry associations forecast the growth rate of FRP pipe productions in the global market. Accordingly, the estimated target of $4.2 billion by 2023 will be attained with a compound annual growth rate (CAGR) of 3.1% from 2018 to 2023 [80]. From the forecast, it was observed that the additional requirement of FRP pipes in the field of oil and gas, irrigation, offshore, chemical and processing industries, petroleum and natural gasoline, and underwater sewage applications is inevitable [81-83].

Among all, the oil and gas sectors create a huge influence on the global FRP pipe market, due to the rise in per capita disposable incomes and an increase in demand for various corrosive mediums. Also, the possibilities of several combinations of FRP composites can facilitate variation in price level which motivates the fuel for oil and gas industry across the world market. The reason for the focus of the oil and gas industry on FRP pipes is mainly due to their contribution to the technical advantages of oil extraction combined with other property enhancement. However, geometric size and fluctuation cost of raw material prices are some of the critical factors that may drag the growth rate of marketing. Furthermore, the proper selection of suitable cost-effective ingredients and the emerging state-of-the-art technology or fabrication methods can reduce the production cost of FRP pipes. All these factors can provide opportunities for the growth of the oil and gas industries to attain a CAGR of 8.4% during the forecast period.

The forecast data was published by the composite piping industries in various aspects, as shown in Fig.3.

3. Relevant reported studies

3.1 Burst analysis on FRP composite pipes

The burst analysis is a very important study needed for composite pipes to predict their real-time performance in the field of oil and gas as well as chemical industries. There are two types of pressure tests, namely; open and closed ends. They can be used to conduct experiment. The performance of composite pipes under varying pressure at room temperature condition as well as hydrothermal condition needs to be studied. Therefore, the influence of different density transport mediums, such as water, hot liquid, gas and chemicals are to be analysed alongside the required parameters. Normally, the piping materials can be subjected to impact loading, due to the sudden fall of any heavy object [84-86]. Similarly, the increasing pressure of transport medium can create the fatigue load under normal and hydrothermal conditions. Furthermore, different support conditions can develop bending moment and compression load in addition to the self-weight of the fluid. Hence, the properties such as low-velocity impact, fatigue, torque, compression and bending moment are important to be studied for the composite pipes with varying internal pressure for suitable applications. Moreover, reports on composite pipes analysed with their wall thickness are also limited. Thick composite cylinders can be analysed by an efficient method proposed by Tsai [87] and theory of Lekhnitskii [88].

The following section addresses the burst analysis of various composite pipes and their scientific findings with suitable justifications. Hawa et al. [89] studied the performance of glass fibre/epoxy composites on burst strength under different energy levels: 5 , 7.5 and 10 J. The filament wound composite pipes with 2.5 mm thick were fabricated at (±55°) winding orientation angle. The results showed that higher damage occurred during higher impact load. Furthermore, the highest axial stress and strain values were noticed at the minimum impact load, which was 50% and 63% higher than the other loadings under static water pressure load. Two different failures, namely; weepage and eruption were noticed in the burst analysis for low and high impact loading conditions, respectively. From the analysis, it was concluded that the burst strength mainly depended upon the damage region of the impacted specimens.

In another study, the burst analysis was carried out with the application of fatigue load on glass/epoxy composite pipe at a winding angle of ±55º using FWM. The internal pressure of 250 bar was applied cyclically with the aid of hydraulic servo valve control. The procedures described in ASTM standard D2992 were followed [90]. Six different fatigue stresses were applied to the samples to find out the failure mechanisms. Consequently, three failure mechanisms: whitening (fibre/matrix interface de-bonding and delamination), pinhole formation and final damage with leakage were observed. This mechanism of failures was demonstrated with the help of photographic images to understand the crack initiation and propagation as shown in Fig.4. The starting point of failure from whitening to delamination are represented in Fig. 4. The propagation of the whitening effect needs to be controlled to achieve the enhanced properties of the composites. The effect of crack orientation on burst strength was experimentally investigated for E-glass/epoxy composite pipes with the winding of ±55°. Static internal pressure was applied using open-ended apparatus. The result revealed that the burst strength increased with an increasing crack angle. The maximum burst strength was observed at the crack angle normal (90°) to the axial direction. Since the axial force was responsible for the hoop stress which could move the crack transversely as the crack angle increased. Also, decreasing crack length due to the increasing crack angle was also another factor for the increased burst strength.

However, the increasing delamination zone was observed for the fixed crack angle with an increased static internal pressure [91].

Gemi et al. [92] studied the effect of burst strength for the impact damaged specimen of filament wound hybrid composite pipes. The functionally graded hybrid (FGH) composites were developed with the combination of glass/carbon fibre and epoxy polymer composite with a varying configuration, such as glass-glass/glass-carbon/carbon-glass/carbon-carbon. The absorbed impact energy of the hybrid composites decreased for high internal pressure due to an increased stiffness of the material. The burst strength of FGH composite pipes was predicted for the impacted specimen at 20 J (maximum energy) with the pre-stressed condition at varying pressure. The pre-stressed pipe at maximum internal pressure of 32 bar showed a better burst strength due to the less damaged area when compared with low pressures of 4 and 16 bars.

Moreover, FGH pipes have influenced by both impact energy as well as burst strength. Especially the presence of carbon fibre at the outer surface exhibited resistance to the radial crack formation against impact load. The glass fibre reinforced epoxy composite pipes were developed and studied for hydrostatic pressure with different end cap thickness [93]. These pipes were manufactured with different interplay design using two woven glass layers (±54°/90°) at the top layer. The failure on the composite pipe occurred at 15 MPa after time of 6 seconds at the lowest thickness. Furthermore, the usage of 60 % volume fraction could be more suitable for this type of structural layer composites due to its better performance against mechanical loading. However, the failure of pipes was discussed in more details using developed modelling.

Thin-walled composite pipes using E-glass and epoxy matrix were fabricated with different angles of ±45°, ±55°, ±60° and ±75° and were subjected to internal pressure [94]. The failure pressure of composites was compared with the pure PVC pipe. Fig. 5a shows the variation of internal pressure for a various winding angle at time response. Better performance of the composite pipe was obtained at winding angle of ±55°, withstanding up to 4.95 MPa pressure level. The failure mechanisms such as matrix cracking and fibre breakage were dominant in all the pipes. However, the burst failure was observed only at the higher winding angle of ±75° (Fig. 5b), whereas the leakage failure (Fig. 5c) occurred in all the composites. They concluded that the composite pipe with liner could offer better performance against burst analysis. Furthermore, it was reported that fibre orientation did not only influence the structural failure, but also the functional failure of the composite pipe.

In addition, the E-glass/epoxy composite pipes were studied on burst analysis depending on temperature concerning symmetric and antisymmetric angle-ply orientations with varying winding angles [95]. A closed-end pressure test was conducted using 25 MPa capacity hydraulic pressure set-up unit with the increment of 1 MPa. Fig.6 shows the burst performance under different conditions. The burst performance was observed to be increased with an increasing winding angle for a single lamina composite pipe, as shown in Fig.6a. Similarly, the influence of burst pressure on symmetric and antisymmetric wound pipes with an increasing winding angle was presented in Fig. 6b. The maximum burst pressure was observed at 55 winding angles at an antisymmetric condition. It was observed that the formation of thermal stress and loss of mechanical properties due to the viscidity of the matrix was attributed to the burst failure at a low pressure.

The fatigue performance of E-glass/epoxy composite pipes was studied using four-layer thickness at ±75° winding angle [96]. The burst failure mechanisms such as whitening, leakage and fracture were analysed for different percentage of internal pressure concerning the ultimate strength of the material. Fig.7 shows the different type of failures for various stress levels with the corresponding number of cycles. They concluded that there was a definite correlation between failure rate and the applied load. The occurrence of failure mechanisms varied and depended on the magnitude of the load. Consequently, the leakage with final failure or bursting of pipes can occur in the case of high load condition.

A similar study was carried out for fatigue analysis by providing elliptical crack at the surface of the E-glass/epoxy composite pipes at the same ±75° winding angle. The effect of depth-to-thickness ratios and depth-to-length ratio on the surface of the composite pipe was analysed concerning the failure mechanism. The failure mechanism such as delamination followed by the Mode-II crack formation and delamination was discussed with respect to crack dimension variables [97]. The effect of varying joint thickness with the number of layers such as eight, five and three was studied for burst strength as well as four-point bending strength with the effect of ultraviolet (UV) curing [98]. The glass vinyl ester/epoxy composite pipes were fabricated with the combination of chopped strands and woven mats as outer surface layers. The maximum burst strength was observed at the five-layer thick joint following with three-layer joint composites. However, it was observed that in the welded pipes, the degree of curing was more important to decide the burst strength rather than the thickness. In the case of higher thickness, the curing was not faster enough between the layers due to the lack of penetration of UV radiation in the radial direction. Furthermore, it was also observed that the load carrying capacity of the composites was not reduced for the lower thickness composites due to the proper load transfer between the layers by mean of effective curing. Eventually, the optimal layer thickness was reduced by using volumetric percentage of reinforcement and in turn the cost of the final product also.

The analytical model was used to demonstrate the flow of hot fluid in carbon/epoxy (T300/LY5052) composite pipes. The elastic performance on thermal stresses and deformations of the pipes under internal pressure assuming convective heat transfer was studied [99]. All the aforementioned properties were carried out for different angle-ply pipe designs, such as +55/-55/+55/-55 (TYPE-A) and +35/-35/90/90 (TYPE-B). The results of hoop stress to strain ratio with respect to the fibre orientation in the axial direction as well as radial direction were observed. Similarly, the shear stress and stain were largely influenced by the stacking sequence. The different stress distributions such as hoop, axial, radial and shear were analysed and presented in Fig. 8 for TYPE-A and TYPE-B stacking sequences. From Fig. 8, it was evident that there was a significant shift in hoop stress value, while the winding angle tended toward circumferential direction increased. Similarly, the shear stress also varied from positive to negative when winding angle was different. It was concluded that the varying winding angle in the circumferential direction and sudden change in ply angle at out layer of the composite pipes were the major factors influencing hoop, axial radial and shear stress as well as the corresponding strains of the composite pipes. In a previous study, the composite pipes were manufactured with aluminium liner with overwrapped carbon/epoxy material at three different sequences of ±50°, ±55° and ±60° [100] . The analytical, numerical and experimental calculations were carried on these composite pipes. The equal amount of sizing pressure of 200 bars was applied on all the three composites to ensure the perfect contact between the composite parts and liners. From the result obtained, it was concluded that the gap between the composite part and liner was increased with a low pressure and the gap was increased at a high pressure. This increasing pressure facilitated the proper load transfer. Furthermore, the analytical model was a best suited model that showed a good agreement with the prototype of seq. 2 (±55°) filled with hydrogen pressure with a higher factor of safety. The proper incorporation of uncertain parameters such as end cap details and material properties of liner, composite part and Tsai Wu criterion into the analytical model further decreased the variation between the experimental and analytical values. A similar kind of work was also reported for aluminium liner with multi-layered composites on burst strength and residual strength. The residual strength of composite pipes was modelled and analysed using two methods of Hencky relation and Ludwick's strain hardening function. The model had a good agreement with the experimentation results [101]. The filament wound composite pipe was developed using a low modulus amorphous carbon fibre and epoxy matrix. It was subjected to the burst analysis after the low-velocity impact test [102,103]. The results showed that more impact energy was absorbed due to the plastic deformation of fibre reinforcement material. Moreover, the absence of fibre breakage at the region of impact load also helpes to decrease the degradation of burst strength of the composite pipe.

Furthermore, basalt fibre reinforcement (BFR) in the epoxy matrix was studied for the optimal winding angle of ±55° and the results obtained was compared with that of glass fibre reinforced polymer (GFRP) [104]. From the results, it was observed that the BFR polymer composite pipes performed better than that of GFR composite pipe. The initial failure of whitening in the BFR composite pipe occur due to the application of internal pressure about 375-390 MPa. Furthermore, the 35% and 13 % of an increase in burst strength and modulus values were observed for BFR composite pipe when compared with GFR composite pipe. Only very few studies have been reported on thermoplastic matrix composite pipes, despite of their recent and wide industrial applications. A study was carried out on the burst analysis with the application of internal pressure and combination of bending moment for steel/polythene reinforced thermoplastic polymer [105]. The burst failure was observed at the ends of the pipes at 18 MPa. On the other hand, the failure was noticed at the middle of the pipe by combining both internal pressure and bending moment, which was more abrupt. The advancement of nanocomposite using E-glass and multi-wall carbon nanotube (MWCNT) modified epoxy matrix was also studied; to analyse its fatigue performance by applying internal pressure [106]. It was observed that the addition of MWCNT in the epoxy matrix at a lower content increased the inter-laminar strength and adhesion between the fibre and the matrix. Also, the main failure mechanism of matrix crack was reduced due to the bridging effect of carbon nanotubes (CNTs) between the fibres. An inclusion of CNT into the polymer matrix blended the crack tip opening and in turn, reduced crack propagation. Thus, it decreased the possibility of delamination and exhibited a significant improvement in burst strength and fatigue life of the pipe.

Similarly, some analytical equations have been developed to predict the stress values of wound pipes under different conditions. The apparent hoop tensile strength of the filament was calculated by using the following Eq. (1) [107,108].

$$\sigma = \frac{F_{MAX}}{2.A_M}. \tag{1}$$

Where σ is the ultimate hoop tensile strength (MPa), F_{MAX} is the maximum load prior to failure recorded in Newton (N), whereas A_M is the minimum cross-sectional area of the two reduced sections, d x b (mm^2).

When two ends of the pipe were closed and subjected to internal pressure, then the tangential or hoop stress acting on the wall thickness is observed to be:

$$\sigma_H = \frac{P}{A} = \frac{pDL}{2Lt} = \frac{pD}{2t} \tag{2}$$

Where L is the length of the pipe, D is the internal diameter, t is the wall thickness and p is the fluid pressure inside the pressure vessel. The longitudinal stress is calculated by using the following Eq. (3) [109]. In general, the axial stress is actually less than the hoop stress.

$$\sigma_A = \frac{P}{A} = \frac{\pi D^2 p}{4\pi D t} = \frac{pD}{4t}. \tag{3}$$

The torque of a pipe was calculated using the following Eq. (4) [110,111].

$$\sigma_A = \frac{\pi}{16}\sigma_{max}\frac{\left(D^4 - d^4\right)}{D}. \tag{4}$$

Where σ_{max} Maximum stress, D = outside diameter and d =internal diameter.

The low-velocity impact energy absorption of the composite was obtained using the following Eq. (5) [40,112].

$$E \frac{m\left(vi^2 - v^2\right)}{2} = mg\delta \tag{5}$$

Where δ = indenter displacement (m), v_i = initial velocity of the impactor body (m/s), v = final velocity (m/s), m = mass of the indenter (kg), g = gravitational acceleration, 9.81 m/s^2.

The incident impact energy (e) was calculated by Rim et al. [113], using Eq. (6).

$$e = mgh \tag{6}$$

Where e = the incident impact energy, m = the mass of the impactor, and g = the acceleration due to gravity, h = the height of the impactor.

The absorbed energy was computed numerically by considering the results obtained from the force-displacement curve by using Eq. (7).

$$W = \int F.ds = F_m\left(S_f - S_i\right). \tag{7}$$

Where W is the total energy absorbed by the impacted pipe, F_m is the applied mean force, S_f is the maximum displacement and S_i is the initial displacement under impact loading [114,115]. All the aforementioned equations provided some preliminary observation based on the geometric and material properties of the pipes under different circumstance.

3.2 Buckling behaviour of composite pipes under different loading conditions

In many circumstances, the FRP composite pipes are used in underground condition to transport hot fluids and gas in oil and chemical industries. Amongst the FRP composite pipes, glass-reinforced plastic (GRP) pipes are increasingly used to transport fluids (oil, seawater, among others) in offshore and marine industries [116].

The underlying composite pipes are generally subjected to axial and compressive stresses [117]. For example, in the application of sub-sea risers, the axial pressures would be expected to rise with the existing severe pressures [116]. These stresses are developed by the axial expansion and contraction of composite pipes due to the existence of hoop and thermal stresses when transporting hot medium at a high pressure. Moreover, the soil load over the composite pipes cannot be uniform so it can exhibit non-uniform distribution load throughout the pipe. A collapse of underground pipes owing to the external pressure has been reported due to these effects on pipes [118]. The overlapping of soil surrounding the composite pipe can constraint the expansion of pipes in circumferential direction due to hoop stress, rather it transforms into axial direction. On the other hand, the pipes can also be fixed with the help of fittings while they needed for a long distance against the wall. Some external compression loadings are also possible to happen in such condition, which lead to the axial deformation in the composite pipes. Furthermore, composite pipes undergone buckling behaviour by the torsion effect which can exist due to the application of structural loading. Various factors such as pipe length, diameter and thickness, reinforcing elements, matrix and type of constraints are factors influencing the buckling behaviour of composite pipes after the torsional loading. A detailed and comprehensive review have been reported [119,120], and the first research work on buckling behaviour of composites was reported by [121].

The experimental investigation of axial deformation on FRP composite pipes filled with different concrete was studied for different categories [122-124]. Fig. 9 shows the E-glass/epoxy FRP composite pipes filled with concrete and subjected to the axial loading along the longitudinal direction with end caps. The performance of different types of concretes confined with composite pipes was studied for axial loading by varying types of cement, compact and non-compact as well as water-cement ratios. A significant increase in axial loading and axial deformation was observed in all the types of concrete with the confinement of E-glass/epoxy FRP composite pipes. Furthermore, the reduction of interfacial slippage was observed in case of Portland cement, been used as core concrete. In addition to the existence of standard failure mechanisms, the phenomenon called splitting was predominant in the case of concrete based FRP composite pipes. However, this material could be a good replacement for steel-based concrete to resist the corrosion behaviour in deep piled column production [125].

The type of failures and performance of E-glass/epoxy composite pipes with multi-angle woven structure were studied using state-of-the art production method [126]. The functional and structural failure modes were measured withrespect to different stress ratios between axial and hoop stresses. The matrix cracking was observed predominantly at an increasing axial stress and fibre breakage was observed more on hoop stress. At same time, in total stress ratio, the enhanced strength was observed for 2/3 hoop stress and 1/3 axial stress conditions, which were the best suitable ratios for pressure vessel applications. Moreover, the lower winding angle of $[\pm30, \pm60_2]_T$) at base lay-up exhibited an increased strength at dominant axial stress, but it was slightly reduced for dominant hoop stress. However, a varying combination of weaving angles ($[\pm 60_3]_T$, $[\pm 45, \pm 60_2]_T$ and $[\pm 30, \pm 60_2]_T$) at the base and top layer angle ply was significantly influenced by the varying loading conditions. A similar kind of study was performed for the same material to analyse the bi-axial fatigue performance with varying hoop-axial stress ratio condition. The stiffness behaviour of the material and the relevant failure mechanism was discussed with respect to the stress ratio [127,128].

The tensile strength of the cylindrical pipe with glass fibre/vinyl-ester was evaluated using ring test. The failure of the pipe was analysed in both radial and axial direction concerning to predict its mechanical properties. It was observed that the damage of the pipe in the depth direction had a direct relation with the tensile strength of the composite pipe. Furthermore, the failure defects such as a cluster of fibre pull-out and delamination were significantly determined by the application of ring test [129]. The progress of crushing behaviour of carbon fibre reinforced matrix composite pipes was studied under the application of tensile loading [130]. Three composites without and with bevel triggers were fabricated with same ply orientation and 65 wt.% of fibre loading. The composite pipes with 45° chambering at one end were called bevel trigger. From the experimental investigation, the brittle crushing behaviour was observed on three failure regions at the interior, middle and external layers. The energy absorption was noticed using the failure of delamination and bending/fracture of the lamina. The benefits such as a constraint to crushing initiation and control of the progress of crushing more stable were noticed for the composite pipes with bevel trigger.

A new study was attempted for filament wound E-glass/vinyl ester composites to predict the failure mechanisms of pipes due to the tensile loading with the support of acoustic emission (AE) sensors [130]. The amplitude of waveforms obtained from the acoustic emission sensors had a good correlation with the failure mechanisms, such as matrix cracking fibre/matrix interface, crack propagations and fibre breakage. This sensor-based signal processing technology can be a good approach for prediction and controlling of failures of filament wound composite pipe. Fig. 10 shows the waveforms obtained from AE sensors and the corresponding failure mechanisms from the microscopic analysis. The performance of various winding angles of ±45°, ±55° and ±63° was studied under multiaxial loading with cyclic pressure loading. The stress ratio was varied for the pure hoop, pure axial and between the range of these two values. The result of the analysis revealed that the optimum performance of winding angles was observed and it varied with the cyclic loading and stress ratio. In each case, three types of failures: leakage initiation, matrix failure and weepage were observed in different stress ratios. However, overall it was concluded that the winding angle and stress ratio were strongly dependence. Accordingly, winding angles of ±45° and ±63° were observed more suitable for axial and hoop loadings, respectively [131].

Four thin walled E-glass epoxy composite pipes with the winding angle of ±45°, ±55°, ±60° and ±75° were studied for various loading conditions at the closed and open end conditions [132]. The correlation between the failure mechanisms for closed and open-end condition was analysed for all the winding angle conditions. From the fracture morphology, the fibre failure was observed and predominate in both closed and open-end conditions. However, it was same for all the cases, because it depended on the applied stress ratio. In the case of hoop stress dominated condition (more than 3 in H: A ratio), two failure planes were observed which was reduced to one in the case of hoop stress (less than two in H: A ratio). It was concluded that it was better to design the composite pipes in the stress value of 2H:1A for the real-time situation in piping industries.

A study was carried out using E-glass fibre and vinyl ester resin produced by the pultrusion method [133]. The buckling performance of the long composite pipes was studied against axial compression alongside the effect of slenderness ratio. The longitudinal and lateral stresses and strains were captured with the support of stain gauges and sensor attached at middle of the tested pipes. From the experimental investigation, it was observed that the composite pipes with low slenderness ratio experienced fracture due to an increased lateral strain by the lateral deformation after buckling. On the other hand, the composite pipes with a high slenderness ratio were subjected to elastic buckling and got ruptured by oversize deformation.

More also, it was understood that the buckling behaviour of composite pipes has been studied under special circumstances, as reported in a few literature. These studies dealt with analytical models, torsional loading and very few were on buckling behaviour of hybrids and natural fibre based composites. Accordingly, the buckling behaviour of anisotropic composite materials was studied, using torsional loading assuming eigenvalue problem with Ritz method [134]. This new method was developed for thick anisotropic composite pipes. It had a good agreement with the existing model and the experimental data for isotropic material, as discussed in the earlier literature. Moreover, this model also included transformation of shear stress theory in addition to the constitutive functional behaviours. Therefore, the outcome of this model was more suitable for any thickness of composite pipe with either anisotropic or isotropic materials. A similar kind of analytical model was also used for the buckling behaviour of a thick composite cylinder, by applying an external pressure [135].

Additionally, a model was developed for polygon composite pipes with torsional loading under the internal pressure, using maximum principal stress and Tsai–Wu criteria. [136]. The effect of varying geometric shapes, fillet radius and winding angles were studied on the shear stress under an application of internal pressure. The minimum torsional shear stress was observed for the circular cross-section with an optimum winding angle between 50^o and 60^o. Moreover, the decreasing shear stress was observed in all the polygon shaped composite pipes, with an exception of the circular pipes, with an increasing fillet radius. Similarly, a joint failure strength of composite pipes has been successfully studied using integrated piezoelectric ceramic adhesive layer and numerical modelling to govern the effects of torsional loading [137,138]. The progression of structural buckling behaviour of long cylinders was reviewed with aid of analytical models by considering axial, compression, torsion and gravity loadings with the effect of friction [139]. Various mode shapes of buckling behaviour of long cylinders using classical Euler beam theory were discussed for isotropic materials with frictionless condition. However, the wave formation and transition from sinusoidal to helical spiral during the buckling effect were not critically explored for the long anisotropic cylinders. Also, it was concluded that the buckling behaviour of short cylinders was not well understood. Moreover, the short cylinders required further studies on various boundary conditions.

The energy absorption of the hybrid composite was studied as an alternative to metal with lower manufacturing cost [140]. Three and five composite pipes were produced using carbon/aramid fibre combination and FWM with varying volume ratio. The relationship between the failure mechanisms and the corresponding energy absorption behaviour for various composites was discussed in details with the help of schematic diagram, as shown in Fig. 11. It was observed that all the composite pipes showed a maximum energy absorption after a long time thermal treatment. Moreover, the energy absorption was observed to significantly vary between the number of layers, layering sequence and thermal treatment. The maximum energy absorption was observed in aramid/carbon three-layer composites. Though, the energy absorption of the composite pipe depends upon the combination of the failure mechanism, the buckling mode absorbs only lower energy. Using provided curvature to the crack front, the energy absorption of the composite pipes can be improved against the buckling behaviour.

Application of uniaxial compression test has been used to study the energy absorption of flax/epoxy composite pipe. The result of the analysis showed that specific absorbed energy of 22 J/g was achieved by the low-density natural flax fibre reinforced epoxy composite pipes, which was close to metal composite pipes, such as stainless steel and aluminum pipes [141]. From the fractured surface, it was observed that an enhanced energy absorption was due to dominant bending and splaying mode of failures. The effect of geometry and material properties of various composites pipes under various test conditions are presented in Table 4.

3.3 Durability properties and their importance on FRP composite pipes

Recently, steel pipes have been partially replaced in sea water pipelines construction due to loss of their strength and life in a shorter period leading to less durability. Steel pipes are corrode easily in seawater and hence, they must be changed periodically to obtain a better performance for fluid transfer. Also, it is very difficult to construct steel pipe under sea water. It requires welding process to connect two steel pipes in some places. Moreover, high skilled labour and high initial cost for construction are needed. To avoid such type of difficulties, selection of FRP pipe is the best alternative for under sea water pipeline. The main advantages of FRP pipe over steel pipe include, but are not limited to less weight, low production and transportation costs, as well as less time required for manufacturing and portability (easy to carry). Also, FRP pipe has more corrosive resistance than steel pipe. Consequently, maintenance cost and heavy repair of the FRP pipes are reduced. The GFRP composite pipes have received more attention in recent years, especially in the construction fields, such as (i) oil and gas industries (ii) infrastructure and

(iii) civil [142]. Besides, the GFRP composite pipes are much more comfortable in terms of: (i) installation (ii) transportation (iii) repairs and (iv) connection than the steel pipes [143].

However, the main drawback of FRP pipe is the moisture absorption. Due to moisture absorption nature of FRP material, it loses its longer durability. The durability of FRP pipe means that the pipe can withstand the load, fluid pressure and resist failure under environmental conditions. The durability of FRP composites pipes mainly depends upon proper design, fabrication and construction. During manufacturing, the selection of winding angle, fibre strength and matrix also play roles in the durability of FRP pipe. In composite pipe manufacturing, the resin is selected upon the areas of application. For example, vinyl ester resin is selected for major corrosive resistant applications. The isophthalic polyester resin is selected when the condition of flowing fluid or liquid is less severe, while the phenolic resin is preferred for fire resistant applications, because phenolic resin has excellent temperature properties and low smoke emissions. The pressurised water pipeline used polyethene (PE) as a matrix to withstand high pressure. Polypropylene water pipe is used to resist chemical corrosion and thermal degradation [144-147].

The main objective of this sub-section is to carry out a detailed report on durability and strength behaviour of filament wound composites pipe under various environmental conditions, such as moisture absorption, seawater ageing, hydrothermal ageing, chemical and acid ageing. Generally, the composites structures loss their strengths and durability properties during their service periods, due to various impacts of surroundings. In water absorption ageing conditions, the moisture degrades the materials. But in hydrothermal ageing, the temperature and moisture both are affecting the materials properties. The seawater, chemical and acid ageing of materials are affected by both moisture and chemical reaction of liquid on materials surfaces. The above ageing conditions decrease the material properties under wet condition. In addition, the composite pipe material also loses strength and stiffness under dry conditions ageing, such as ultraviolet radiation and thermal ageing. In ultraviolet (UV) weather condition, the photo-radiation and temperature have combined effect to change appearance of the materials and decrease the strength of the materials. Generally, the FRP pipe has more stiffness and strength-to-weight ratio and chemical stability [148-150].

However, the strength and stiffness of FRP pipe are degraded by infusion of water molecules or liquid into materials. Most of the FRP materials are used in the oil and gas industries, manufacturing tank, chemical and acid industries and cable lining under sea water. In these areas of application, liquid mainly plays a significant role to degrade the materials by creating matrix corrosion and swelling on it. The moisture diffuses into the FRP materials and changes their mechanical and physical properties [151,152]. Most of the investigators noted that moisture intake could also change the thermal expansion coefficient of fibre-matrix [148]. At the end, the materials will experience catastrophic failure. Hence, it is important to predict the life of FRP structures under various accelerated ageing conditions. Several articles reported that the strength of composites materials depends on better interfacial bonding between fibre and matrix. Interfacial bonding mechanism is important for obtaining long durability. This bonding mechanism is deteriorated by surface change in matrix and degradation [153-157]. It is essential to monitor the change of bonding mechanism occurs in the matrix, because a better load transfer is achieved between fibre and matrix through bonding mechanism [150]. Recently, a study on durability of glass epoxy pipes under sea water exposure was carried out by Mehmet et al. [147]. They predicted the failure pressure under sea water exposure for 3, 6 and 9 months according to ASTM D1141 standards test method. The static pressure test was conducted on sea water aged specimen, impacted and non-impacted specimens. Fig. 12 shows the hydraulic static stress apparatus for FRP pipe. It supplied the pressurised hydraulic fluid into the closed pipe. The pressure of the fluid was controlled. After the static pressure test, they observed leakages and eruption was observed in non-impacted samples at the end of the specimens. However, these types of failure were observed in impacted samples around the impacted zone. This failure was attributed to occurrence of matrix crack, fibre breakage and de-bonding. Apart from environmental ageing, the fatigue and stress cycle also exposed the materials to damage.

Mehmet, et al. [158] studied the sea water effects on fatigue life of glass fibre reinforced epoxy pipes subjected to impact loading. Initially, the fabricated FRP pipes were immersed in seawater for 3, 6 and 9 months. Later the aged pipes were subjected to impact loading of 5, 7 and 10 J. After impact test, they conducted the fatigue test for impacted specimens, sea water aged specimens and non-impacted specimens according to ASTM D2992 standard. They carried out fatigue life cycle on the various aged specimens. They concluded that the fatigue life increased up to 3 months ageing of impacted specimens, later it was decreased by increasing the exposure time. Moreover, 3 months aged specimens had more elastic. After 3 months, further aged specimens have less fatigue life cycle due to more absorption of sea water. The long-time immersion specimen had de-bonding between fibre and matrix. Moreover, matrix corrosions and damage were also observed.

Thermal and hydrothermal ageing also affected the FRP pipe and reduced the durability of FRP pipe. Under long term thermal ageing conditions, the mechanical and thermal properties of composites were deteriorated due to thermal degradation. Moreover, surface morphology of composites pipe also changed due to the effect of plasticisation of the matrix. Most of the pipe was exposed to thermomechanical loading due to the hot and cold fluid flew inside the pipes, which gradually decreased the strength and durabilities of the FRP pipes [159]. In general, when thermal ageing time was increased, an expansion in crystallinity, molecular weight, chain scission, hydroxyl and carbonyl groups as well as more crack surfaces were observed [160-162]. It is essential to study the mechanical behaviour of composites pipes and to understand the properties change with respect to temperature change. These are needed to develop the material design of FRP pipe for oil and offshore main application [159]. In a previous study [163], thermal exposure behaviour of glass/epoxy composites pipe under various temperature conditions was studied. They developed the composites with diameter, thickness and winding angle of 86 mm, 6.2 mm and 55^{o}, respectively. They conducted the thermal ageing conditions from -40 ^{o}C to 80 ^{o}C for 8 hours with the help of SERVONTAN climatic chamber and then performed the uniaxial test. Fig. 13 depicts the thermally aged specimens and its failure mechanism developed on the glass/epoxy pipe for various temperature conditions. The experimental results showed that the degradation of mechanical properties was observed with as increased temperature. The rigidity of composites was increased under cold chamber conditioned samples due to low displacement at the break.

Moreover, another work was carried out by Jong et al. [164]. They prepared pipe structure using polyethene and exposed it to thermal ageing at 100 ^{o}C for 720, 2400, 6000 and 7200 hours. After the exposure, the mechanical properties and thermal behaviours of the pipe were tested. They concluded that the properties of the pipe materials degraded due to thermal ageing and the ductile properties of the material transitted into brittle fracture, due to a decrease in elongation at break under thermal exposure time. Reiz et al. [165] conducted the burst strength of glass fibre reinforced composites pipe under accelerated ageing conditions by combining hydrostatic pressure and temperature conditions, according to ASTM D1599 standard. During ageing, the pressurised water of 1 MPa was filled in glass FRP pipe with water temperature of 80 ^{o}C. They performed the ageing process for 2, 4 and 6 months. After ageing and burst tests, they further conducted the tensile test for aged specimens. The results revealed that the ageing process weakened the FRP pipe and affected the stiffness and strength with respect to time. The strength reduction of 30% was recorded on aged specimen when compared with the unaged specimen. In another study that was conducted by Hawa et al. [114]. They conducted the hydrothermal ageing for 500, 1000 and 1500 hours. After ageing, the impact tests with loads of 5, 7.5 and 10 J were conducted. They reported that the impact damage area of FRP pipe increased when ageing period increased, as shown in Fig. 14. Moreover, the damaged area increased with an increased impact loading.

The pipe winding angle orientation (symmetric/antisymmetric) and utilisation of pipe under various atmospheric temperature conditions also influenced the durability of FRP pipe. Therefore, it is essential to study the characterisation of FRP pipe in different atmospheric temperature conditions. Onder et al. [95] studied the effect temperature and winding angle for filament wound composites structures. They fabricate the composites with 45^{o}, 55^{o}, 60^{o}, 75^{o} and 88^{o} with symmetrically and antisymmetrically orientations. They conducted burst failure test and observed that the best properties was observed with winding angle of 55^{o}. They observed that all the winding angle of FRP structures did not cause a failure in the same manner. Moreover, different winding of FRP pipe failed in different burst pressure. Initially, the burst failure pressure was increased to 55^{o} later, as the burst failure pressure was gradually decreased. They also conducted the burst failure test on various temperature and different winding angle conditions. Fig. 15 shows the burst failure analysis for various temperature conditions. The authors predicted a better burst failure temperature at 20 ^{o}C,. Thereafter, the burst failure pressure decreased with an increasing temperature conditions. Most of the research articles reported that the temperature caused deteriorated properties and reduced durability of the FRP composites, due to thermal degradation [150,163,166-168].

Moving forward, the FRP pipe is used in chemical industries for transporting chemicals and acids from one place to another. During transportation, the chemical or acid reacts with the polymer matrix. The properties of pipe and surface morphology are damage due to chemical reaction. This acid attack can create the rough surface by corrosion of fibre and matrix on FRP pipe. As a result, the pipe experienced sudden failure in a short time. The main reason is that the pipe carries a higher pH concentration of acid in some cases. The pH level of acid is also one of the factors for deterioration of composite pipe structure. Low pH concentration of acid will not cause a severe attack on pipe structure [169-171]. The water industries use the FRP pipe for fluid transportation. The water contains chlorine, therefore it also affects the inner wall of the pipes. Most of the researchers reported that the chlorinated water of 0.5-3 ppm; pH = 6.5 and 6.8 reacted with FRP pipe wall and created cracks initiation at the degraded inner wall surface [172,173]. In another study reported by Rehab et.al [174], they observed that strongly oxidizing acids attacked on polymer pipe provoking major changes in mechanical properties throughout the pipe wall. More over, the stress and strain components of polymer pipe gradually decreased when exposed to the toluene-methanol and sulphuric acid environments. The hardness and roughness of polymer composites pipe changed when FRP was exposed to diluted hydrochloric acid [175]. The chemical degradation was caused by thermal oxidation. The oxidation process damaged the inner surfaces of the pipe [176]. However, this type of failure in polymer composites was rectified by applying antioxidants; nanoclay or gel coating on polymer matrix and prevented the acid moisture intake into fibre-matrix bonding mechanism. Moreover, this coating resisted the surface corrosion of the fibre reinforced polymer composites. Most of the researchers reported that the fibre and matrix interfacial bonding was strengthened by an addition of nanoparticles in matrix materials [176-179]. Table 5 shows the various ageing conditions of FRP pipe and their failure conditions are listed. Most of the investigators observed that the degradation of mechanical properties was due to loss of structural integrity on FRP pipe.

3.4 Performance of FRP composite pipes under various corrosion environments

Pipelines transporting and distributing oil, gas, water, petroleum products, chemicals, steam and other substances are of fundamental importance to most economies worldwide. The pipelines are an essential part of our infrastructure. However, the integrity of these assets is seriously affected by electrochemical deterioration called corrosion [180]. Many researchers measured the performance of FRP pipes in corrosive environments, such as hydrochloric acid, sodium hydroxide and acidic solutions. Their results depicted that an increase in the exposure time in corrosive environments led to a decrease in the performance of FRP composites [181,182].

Pipeline corrosion and sometimes resulting failures, as well as possible repairs and monitoring costs, cost the global economy billions of dollars yearly [183]. The safety of pipelines is paramount in the case of pipelines carrying flammable, explosive and potentially contaminating fluid (liquid or gas). Corrosion factor is extremely important for the oil and gas industry to design and select the best available pipeline systems as well as materials and their corrosion protection systems. Pipeline corrosion occurs, because of an electrochemical reaction in the presence of an electrolyte in a watery medium, usually soil water or fractions of the products it transports. Transfer of electrons is a very important part of the corrosion process. The corrosion rate of a piping system is usually associated with external and internal factors. External factors include (i) soil chemistry, (ii) working environment and (iii) moisture for buried pipes or water chemistry in the case of submerged pipes. Internal factors contribute to corrosion may include (i) the oxygen content or reactivity of transported liquids and gases, (ii) the use of dissimilar metals in the piping system, (iii) the temperature, (iv) flow rate and (v) pressure of fluids and gases. Fig. 16 shows the common forms of pipeline corrosion and subsequently explained briefly.

Uniform corrosion: Causes uniform material loss on the pipe surface, leading to a continuous thinning of the pipe wall, as shown in Fig. 16a). By selecting an appropriate pipe material and combining corrosion protection methods, such as cathodic protection and surface coatings, this type of deterioration can be mitigated or even prevented on the external pipe surface.

Pitting corrosion: It is the most common form of corrosion in pipelines for the transportation of oil and gas. The severe deterioration of a local surface leads to the formation of a cavity or pit on the surface of a pipe (Fig. 16b). This corrosion type can be prevented by selecting the right pipe material for a particular service environment. The use of cathodic protection can also mitigate pitting corrosion.

Cavitation: Cavitation damage occurs on the inner surface of the pipeline when the operating pressure of the fluid falls below its vapour pressure, resulting in the formation of vapour pockets and vapour bubbles, collapsing on the inner surface of the pipeline. It can lead to erosion corrosion (Fig. 16c). Pipeline components, such as (i) tees or transition joints, (ii) elbows, (iii) discharge pipes, (iv) pump suction, among others are sources or susceptible locations of this type of damage, depending on the operating conditions. Reducing the fluid pressure gradients and preventing drops in the vapour pressure range of liquid, the cavitation can be prevented in pipelines.

Erosion corrosion: It is usually caused by the relative movement of fluid and particles on the inner surface of the pipe. Fluid turbulence can lead to a rapid increase in the rate of erosion. Poorly finished inner pipe surfaces or pits that interferes with the smooth flow of fluid can lead to localised turbulence. It could lead to high erosion rates. In addition to careful design, the selection of wear-resistant materials can prevent or reduce cavitation in combination with erosion corrosion.

Stray current corrosion: It occurs on the external surface of a pipe due to the flow of stray currents through the pipelines. The damage can be reduced by governing the leakage of electricity, by passing the stray current to an earth station or by using an additional protection system.

Microbiologically-influenced corrosion (MIC): It is the weakening of the metal by corrosion processes that happen directly or indirectly as a result of microorganisms' metabolic activity. A typical image of a corrosion pit formed by MIC is shown in Fig. 16e.

A single chemical process may be mistakenly assumed to involve the corrosion phenomena. Several mechanisms of corrosion include crevice, galvanic, erosion, inter-granular, stress and selective leaching corrosion [184]. Researchers have explained the vulnerable weakness of steel pipe to be corrosion and metal loss, due to laying the steel pipes in underwater and underground [185,186]. Though, the steel pipe possesses high strength, low density and easy of joints, it has some serious problems in the form of dents, crack, buckling, wearing, spalling, leaks, rupture and gouging [187]. Therefore, researchers have studied alternative materials that are (i) have effective repair solution (ii) easy to use and (iii) relatively light.

FRP composites have a long history of combating corrosion [188]. Repairing the corroded parts in the pipeline often involves closing the line, cutting the damaged section, and welding in a new section. Due to the unexpected failure which leads to loss of production and revenue. In recent years, the development and application of fibre reinforced polymer composites, which are often used to strengthen corroded metallic pipelines, has been growing rapidly [43]. Composite overwrap repair systems for fibre-reinforced polymer composites have recently been introduced and widely accepted as an alternative repair system for pipelines. FRP material gives some advantages in repair over the conventional techniques. These advantages are (i) repair is quicker, (ii) the corroded pipe can be operated while the repair is being carried out, (iii) fire and explosion risks due to welding or cutting are eliminated, (iv) economical to repair. Furthermore, the FRP composite repair was observed to be 24% cheaper than the welded steel sleeve repair and 73% cheaper than the replacement of the defected pipe section [189]. The use of FRP composites in corroded pipes have been incorporated into the American Society of Mechanical Engineers (ASME) ASME B31.4 [190], ASME B31.8 [191] pipeline codes and in CSA Z662 [192]. Composites made by using glass fibre/polyurethane matrix can be applied to the corroded portions for most of the materials.

The materials include concrete, metal, PVC and composite. In a previous work of da Costa Mattos et al. [43], they examined the glass fibre reinforced polyurethane repair systems for metal pipelines with localised corrosion damage that impair operability. There are various commercial repair systems based on fibre-reinforced composite materials: (a) dry fibreglass/liquid resin composite wrapped over the corroded part, (b) ready-made pre-cured layers to be wrapped around the pipe, and (c) pre-impregnated flexible resin bandage to be wrapped in water. Well performed repairs by using FRP composites usually offer (i) corrosion resistance, (ii) fuel and water resistance, (iii) thermal tolerance, (iv) good chemical resistance and (v) abrasion resistance. In addition to corrosion-related problems, the FRP pipes are subject to various experimental studies [157,159,188,193-195]. The details of such studies included fatigue and burn test on carbon fibre/polymer [193,196], creep analysis on glass fibre/epoxy [194,197], impact analysis on glass fibre/epoxy [188], thermo-mechanical test on glass fibre/epoxy [159], hydrothermal ageing on glass fibre/epoxy [195], and physical property on glass fibre/vinyl ester [157]. Although FRP composites are used in varieties of studies, this particular section focuses on their corrosion performance. Glass fibre reinforced plastics has been increasingly used in a wide range of high-tech engineering applications, such as pipeline reinforcement as primary load bearing structures.

Additionally, Ghareba et al. [198] explained the common types of corrosion occurrences in the petroleum industry, especially in pipelines. This type of corrosion depends primarily on composition of oil. Carbon dioxide corrosion, commonly referred to as sweet corrosion, is one of the most serious corrosion forms in the oil and gas as well as transport industries. Da Costa-Mattos et al. [47] tested towards safer and more reliable procedures for the application of epoxy repair systems in metal pipelines with localised corrosion damage. Duell et al. [199] developed a new method to arrest the corrosion externally and structurally reinforced steel pipes by an external wrapping of damaged sections by using fibre reinforced polymer composites. Another study, Watanabe Junior et al. [200] proposed a composite repair system based on polymers that are economically interesting for the oil industry to repair localised corroded circumferential welds in super duplex stainless steel pipes. Fibreglass tape with water-activated polyurethane resin mixed composite of number of layers of 12 and thickness of 0.33 mm each was wrapped over the pipe to repair, whereas the fibres were oriented between 0° and 90°. A simple methodology was proposed to estimate the failure pressure of thin-walled metal pipelines with arbitrary localised corrosion damage [201,202]. Da Costa Mattos et al. [203] used special epoxy systems to repair water pipeline failures. They tested the strength of the corroded portions of the pipeline after using epoxy. Fig. 17a shows that an offshore repair was applied to an externally corroded pipe by using unidirectional glass fibre laminate. Fig. 17b shows the repair of complex shape, such as tee on 400 mm pipe by using glass/epoxy fibre composites [204]. More studies on fibre-reinforced composite repairs of pipes have been reported [196,197,205]. Alexander [206] developed carbon/E-glass hybrid composite system for repairing corroded offshore risers. Risers are subject to degradation mechanisms during operation, including external corrosion and mechanical damage owing to contact with external forces.

Tian and Cheng [207] improved the resistance of hydro transport pipe steel against corrosion and erosion in oil sand slurry by using electrolytic deposition of Ni-Co/Al_2O_3 composite coat. ARAl–Sarraf, and Yaseen [208], reduced the growth of metallic corrosion in oil pipelines provided by two groups of internal coatings. The coatings include nitrocellulose and sodium silicate. From their work, it was revealed that the coated composites exhibited higher in corrosive resistance than the uncoated ones. Mertiny et al. [209] observed accelerated pipe erosion in slurry hydro-transport pipe structures due to the corrosive environment. To resolve this problem, the researchers developed an innovative pipe system consisting of external and internal portions. The former one was made up of load-bearing filament wound thermoset pipe, and the latter one was corrosive resistant polyurethane liner. The developed piping system efficiently prevented catastrophic liner failure provided by the pressurised gases and fluids trapped between the liner and pipe interface.

Majid et al. [210] studied to understand the cause of pipe failure held in Northern part of Malaysia, which disrupted the natural gas supply for 7 hours. Three pipes were involved in this incident, and these pipes were laid adjacent to each other. The natural gas was transported through the medium density polyethene pipe (MDPE) of the three pipes. NASTRAN software was used as one of the methods to explore the potential for failure by analysing the stresses surrounding the pipes. It was revealed that owing to the corrosive effect, the thickness of the pipe decreased significantly caused the pipe to fail. Mertz and Gillespie [211] explained how the galvanic corrosion between carbon and steel could occur. A layer of E-glass FRP material was recommended to insulate both materials electrically to prevent this occurrence. Seica et al. [212] developed tubular steel structures with carbon fibre/epoxy composites for underwater applications. The steel structures suffer further corrosion damage, and the use of scaffolding and heavy machinery and long service interruptions are often required for this repair method. Therefore, a newly developed carbon fibre reinforced epoxy composite rehabilitation methods have no such disadvantages.

3.5 Recent advancements in numerical simulation on FRP composite pipes

By the evolution of computers and their processing capability, the numerical simulation was applied drastically in the area of science and technology in the past three decades. The numerical analysis was performed using much software, including ABAQUS, ANSYS, I-DEAS and also using in-house developed programmes [213]. The finite element method (FEM) was initially applied to aircraft structural and for aerodynamics application using supercomputers.

Later, it has expanded its wings to other engineering applications, such as civil, automobile, machining and other related fields. The analysis of pipes using FEM plays a vital role in research to reduce the cost of real-time analysis [214-216]. It also reveals the initial results of the material. The application of FEM in the analysis of pipe under construction sector started in the late sixties [217], the analysis of the embankments to calculate stress, strain and displacement under the assumption of plain stress and isotropic condition. The FEM is the most commonly used numerical technique for solving piping problems in many industries such as marine, oil and gas, automotive and chemical. The FEM technique can be used in (i) heat transfer analysis (ii) plastic and creep analysis (iii) dynamic analysis, among other applications. Moreover, a comprehensive review of the finite element analysis of pipes was covered from 1997 to 2004 by Mackerle in [218-221].

The computer simulation programme LSBUILD, FEMINT, SLAE with a seven number of inbuilt subprogrammes were developed based on the early programme concepts and developed by various researchers who are good at finite element method. These early numerical simulations lay a platform for the researchers to continue their research in the field of culverts and composite pipes, and later it expanded to FRP pipes.

Some of the researchers started using these methods for analysing culverts [222]. The stress developed and the displacement of soil culvert system under loading conditions were also studied by another researcher [223]. The actual numerical solution of composite pipes was pioneered by Katona et al. [224]. They developed a computer simulation programme using finite element method, namely CANDE (Culvert Analysis and Design) and commercially available over 40 years for testing and improvement. Katona also analysed different types of materials, including plastics and other composite materials. After the diversified research initiatives in different segments of piping applications, the research progressed to fibre reinforced pipes in early 80s [225]. This gave the space for the development of further research in the field of pressure vessels and boilers, using FRP pipes. This kind of research with FEM also progressed and assisted in recent research in which they predicted the burst pressure of a FRP pipe, using a split-D tension test [226]. This method was used for a 2D plane strain and rod elements to predict the hydrostatic pressure of the pipe.

Glass fibre reinforced composite pipes were used as an alternative material for steel pipe in many applications to benefits from their anti-corrosion property and low cost. Difficulties regarding manufacturing the composite were eliminated by the advancement in the manufacturing methods of composites. Fabrication of composites using thermoset and/or thermoplastic as a matrix was majorly adapted. The analysis of the glass pipes was initiated by Highton et al. in the late 70s [227]. They started work with the glass and epoxy composite material pipe. The simple elastic FEM programme was developed to measure the interlinear shear stress and strain in a 75^{o} filament pipe. The internal pressure and axial load were given to the specimen, and the failure length was measured using the programmeme. Using the same programmeme, Soden et al. [228] analysed the E-glass/epoxy composite tube with filament winding angle of 55^{o}. The pipe was subjected to internal pressure, axial compressive and tensile load. Failure modes of the specimen were compared with experimental and numerical results. In the same period Sharp et al. [229] developed a glass fibre reinforced plastic. The stress, strain and displacement values were computed using the finite element method. These values were compared with the physical or experimental test conducted for the FRP pipe under the buried soil box of four types and different loading conditions. The FEA values and the physical test values were closely agreed. Later in 1900s Mistry et al. [230] theoretically investigated the suitable winding angle for glass FRP pipe under the external pressure and axial compression. Under the hydrostatic pressure condition, the optimum angle of winding was calculated as 80^{o} using finite element method. Similarly, the carbon FRP tube was subjected to biaxial stress by inducing axial load and internal pressure. Abdelhaq et al. [231] worked with glass fibre and polyester resin with the help of ABAQUS software. They used 8-node plain strain element and solved it as a non-linear function. Hence, they were able to study the crack propagation in the composite.

In the 20th century, many researchers started to work on the numerical analysis of FRP pipes. Some of the major research works were reviewed in this paper. For example, Mamalis et al. [232] studied the crush behaviour of the glass/polyester composite tube. The finite element MARC code was used for the analysis by considering the pipe as a three-dimensional component, where the majority of the material was framed as 8-node brick elements. The load and velocity were the major input parameters along with other boundary conditions. Energy absorption characteristics, deformation of the material and the crushing mechanism were clearly understood, using this analysis. To understand the internal pressure ratings for UV curing process, Pang et al. [233] prepared a composite pipe using E-glass reinforced with epoxy vinyl ester resin. These composites were tested using the COSMOS programme. The component was tested as a three-dimensional model using 8-node element, where pressure was given as an input to study the shear and peel stresses. Kochekseraii et al. [234] analysed the glass fibre reinforced with polyvinyl chloride pipe flexural behaviour, using the ABAQUS FE programme. The pipe was considered as the isoperimetric shell element and subjected to bending in the plane as well as internal pressure. The displacement regarding small and large was measured and also compared with the experimental results. The damage study of the composite was also conducted using FEM programmemes, whereas Trafaoui et al. [235] analysed the glass reinforced epoxy tube using ABAQUS 6.2 programmeme for static and dynamic finite element test. The three-dimensional model with hexahedral and tetrahedral solid elements was used to analyse the component. The impact energy loading was applied on the specimen, and the load and displacement were measured to understand the occurrence of the damage limit on the specimen. The filament wound glass/epoxy composite pipe was numerically tested by Perillo et al. [236], using ABAQUS Explicit programmeme. Considering the pipe as a three-dimensional solid hexahedral element, interlaminar damaged was studied with the help of drop weight model. Impact time and force were accurately predicted using the FE model.

Thermal analysis of the composite pipes was also explored to understand the curing process during internal heating. Xu et al. [237] developed a glass/epoxy composite tube and analysed it, using ANSYS programme. The thermochemistry model was adapted for the study, and the pipe was considered as a plane 55 axial symmetry element. Thermal conductivity and the curing time were observed in the analysis to understand the temperature behaviour. Also, the vibration analysis was performed by Khulief et al. [238]. They formulated an elastodynamic model using wavelet-based FE method. The natural frequency of the glass/epoxy composite was tested under three boundary conditions, and the pipe was considered as a SHELL 281 element. The natural frequency of the specimen was validated by experimental and numerical methods. The results obtained were observed to be accurate using the developed FE method. Recently, Sulu et al. [239] analysed the composite pipes made up of E-glass and epoxy sliced into three pieces with three orientation angles. Using ANSYS software, the pipe was modelled as 20 nodes isoperimetric quadrangular element. The internal pressure was applied to understand the stress behaviour of the material. The optimal orientation and suitable adhesives were selected using this analysis. In another recent study, Toh et al. [240] investigated both the composite pipe and steel pipe under buried conditions. Three-dimensional finite element model was created and Mohr-Coulomb plasticity soil model with different supported conditions was adopted. The geostatic stress and the displacement plot were studied to understand the effects of land slide and heavy rainfall.

The use of carbon fibre is growing along with glass fibre, but due to cost consideration, the research works available using these fibres are minimal. To avoid the failure of pipe materials under subsea and gas piping system, these materials are widely used. Earlier research was mainly on carbon. For instance, Amaldi et al. [241] investigated the tube made up of carbon fibre reinforced epoxy composite using CASTEM 2000 software. The biaxial stress was induced by applying axial load and internal pressure. Three-dimensional model was developed and the shell element was used to study the elastic behaviour of the object. Moreover, the analysis was made based on the different woven angles All the numerical results obtained were compared with the experimental values. Another researcher evaluated the basic stress distribution of the carbon fibre reinforced polymer (CFRP) pipe in the adhesive layer while subjected to fatigue test [242]. Adhesively bonded CFRP was used in other work, and they investigated the fatigue strength under rotating bending fatigue test [243]. The FEM code MARC was used to calculate the stress distribution in the same environment and the error obtained between experimental and mathematical models. Therefore, the crack initiation and its propagation time were obtained. The test specimen was considered as an isoperimetric and axisymmetric element.

The dynamic analysis of the pipe was also performed by Jerome et al. [244], using an in-house developed programme and advanced software. They analysed an externally reinforced concrete with carbon fibre reinforced epoxy. An automatic dynamic Incremental non-linear analysis (ADINA) code was used, and the specimen was considered as a hypo elastic model. The dynamic behaviour of the beam was studied using FEM. They were compared to the plain beam and externally reinforced beam. The displacement and time behaviour was determined by the numerical simulation and also compared with experimental results obtained. In addition to the normal stress and deformation behaviour studies, the research was conducted to investigate into the impact behaviour of the composite pipe. Kim et al. [245] investigated a carbon composite cylindrical shell using a finite element C programme to identify the dynamic response during impact loading condition. This non-linear equation was resolved using the Newton-Raphson method, and the results supported that an increase of curvature could take up more contact force. Both structural and thermal analyses can be performed simultaneously for the composite problems. For example, Holstein et al. [246] conducted a numerical and experimental analyses on carbon reinforced epoxy tubes. Two types of tubes were developed with different grades of carbon fibre and epoxy. Software package ANSYS and I-DEAS were deployed to analyse these two types of tubes, using the 2D shell and 3D brick elements, the experimental values were similar to ANSYS results. The deviation was observed in the I-DEAS package. The thermal deflection was studied by the addition of varying thermal load and displacement. Table 6 depicts the different types of software tools used for numerical analysis of FRP composite pipes. The data on types of elements and the parameters used for the numerical analysis of various materials are presented in Table 6.

A novel concept of un-bonded flexible pipe named as FLEXTREME made up of carbon fibre and the polymeric liner was presented by Rytter et al. [247]. This pipe was analysed using the ANSYS programme, where all the components were considered as the two-dimensional axis symmetric object. The external pressure was applied to the pipe, and the behaviour regarding the contact pressure was reported. Vedvik et al. [248] analysed the carbon/epoxy composite tube along with steel liner to evaluate its cracking and damage. ANSYS software was used to analyse the pipe, using 8-node element as a three-dimensional object. The load and internal pressure were given to understand the crack behaviours in two types of lay-up patterns. Graphite also was used by many researchers to analyse the strength of the FRP pipes. The weight-to-strength ratio and corrosion resistance always attract the researchers to use these composite materials. Rizzo et al. [249] analysed a graphite specimen using an elastic FEM programme. Then, the same programme was used by other researchers to calculated stress and displacement for glass fibre composite tubes. The stress distribution of the composite was determined by using a shell theory. Palazzoto et al. [250] studied the impact behaviour of the graphite reinforced epoxy cylindrical shell using an in-house finite element code developed by the authors. This code was used to make a comparative study of experimental impact test and the numerical analysis. The object was modelled with six different lay-up pattern and considered a 36 DOF shell element. After the application of boundary conditions, the results obtained were plotted to understand the radial peak displacement, cracking and delamination. Rao et al. [251] analysed a taper composite tube laminated by graphite/epoxy material, using ANSYS. It was considered as an isotropic SOLID 95 element, and the forces were applied on the model. The shear stress and displacement effect in the taper angles were measured and tabulated. Das et al. [252] revealed a suitable stacking sequence for bonded pipes made up of graphite and epoxy composite. The stress analysis under the high internal pressure was performed, using ANSYS 14.0 and considering the specimen as a three-dimensional 8-node brick element.

Moreover, a comparative study of carbon and glass fibre pipes has been conducted earlier by Fazal et al. [253]. They determined the most influential factor for energy absorption capability of glass fibre and carbon fibre reinforced composite tubes. The modelling and analysis were carried out using the ANSYS software, and the results obtained were compared with previous experimental results. An artificial neural network programme was used to identify the influential parameter among a number of layers, stacking sequence and layer thickness of the composite. The theoretical studies of the composite pipes were done by some researchers to reveal the behaviour of the composites under different boundary values. For example, Kistler et al. [254] modelled a cylindrical shell element as a laminate structure and analysed the same a non-linear structure, using ABAQUS software. The modelling chose the 6 nodes triangular shell element and other boundary conditions were imposed to study the impact force and displacement. Boot et al. [255] calculated the creep behaviour of a thin wall polymeric pipe, using a non-linear elastic system. The constant hydrostatic pressure applied in the model for the long term and the simulation were studied.

4. Future outlooks and challenges

Although, there are several composite materials used by the piping industries, but the exploration of those materials regarding scientific research have not extensively reviewed. From the detailed literature analysis, it was observed that the burst analysis was mostly studied for glass/epoxy composite pipes under different conditions. Hence, there is a scope for the composite pipe production using other synthetic fibres, such as basalt, kevlar and aramid fibres for a large scale loading applications. Though, few hybrid composite pipes underwent some impact studies, there is still much to cover concerning production of hybrid composite pipes using various combination of fibres. The combination of synthetic/synthetic, synthetic/natural and natural/natural fibre can be developed to perform burst analysis. Furthermore, the effect of chemical and UV radiation treatments on both synthetic and natural fibres can also be studied to include burst, buckling, durability and corrosion analysis. From the reviewed studies, it was evident that most of the composite pipes failed by following the route of resulting in the effect called whitening, leakage and final fracture. Moreover, the failure mechanisms such as matrix cracking and fibre breakage were observed as predominant. It was observed that all the aforementioned failure mechanisms decreased with the addition of nanoparticles. Hence, the blending of different nanoparticles such as MMT nanoclay, other metal and ceramic can be studied with thermoset polymer matrices: epoxy, polyester and vinyl ester polymer matrix, to mention but a few. Furthermore, these nanoparticles can also be analysed to investigate into the effect of varying particle size, shape and dispersion mechanism on the properties of the filament wound FRP composite pipes.

The buckling behaviour of composite pipes under different loading conditions, such as uniaxial tension and compression loadings have been widely studied mainly on E-glass fibre reinforced epoxy composite pipes. The exact stress ratio development during the real condition can be analysed with more realistic data in place of approximate stress ratio between hoop stress and axial stress. Moreover, the buckling behaviour of composite pipes due to an application of torsional load has not been well explored, using experimental investigations. By providing the chambering at the sides of the pipes can control the propagation of the central crack front, which led to an enhanced energy absorption by buckling. Based on the extensive literature survey, it was evident that the durability of FRP pipes could be decreased due to the infusion of moisture into matrix, swelling, acid stress corrosion, chain scission and plasticisation on the polymer and microcrack on surfaces of FRP pipe. These types of failure affect the mechanical properties and lead to loss of structural integrity. However, these types of defects can be controlled to achieve an improved durability of FRP by strengthening the fibre-matrix interfacial bonding. Most of the articles reported the durability studies on mono-fibre reinforced polymer pipe. Few works were only carried out on hybrid fibre reinforced polymer composite pipe structures. Much studies are yet to be covered on hybrid FRP pipe. Many researchers reported that the durability properties depended on thermal and hydrothermal ageing, sea water ageing and acid ageing. Few studies were only carried out on the durability of FRP pipe when exposed to ultraviolet radiation. There is no critical study carried out on fire resistant properties of hybrid FRP pipe under long term hot flue gas exposure.

Also, many researchers have developed a fibre-reinforced polymer composite overwrap system to reduce corrosion in pipelines and to repair the structures. This overwrapping system was widely accepted as an alternative method for repairing pipes rather than replacing the entire pipe with a new one. This overwrap was designed by FRP manufacturer and included in ASME standard. Researchers have used composite coatings in oil pipelines and demonstrated that coated composites had a higher resistance to corrosion than uncoated composites. It can, therefore, be concluded that FRP composites are used to increase corrosion resistance in structural elements in air, underwater, underground and such like for the transportation and distribution of oil, gas, water, oil products, chemicals and steam.

5. Conclusions

FRP composite pipes have been used in several pipeline industries in the last two decades to transport fluids (liquids and gases) in forms of oils, water (hot and steam), petroleum products and chemicals, among others. In particular, lightweight FRP composite pipes are getting more attractive in the oil and natural gas industries, due to their significant advantages such as corrosion resistance and structural flexibility, lower transport and production cost, lower weight to higher specific strength, ease of repairs or maintenance and high durability against unfavourable weather condition. These inherent properties of FRP filament wound composite pipes are extremely difficult to obtain in metallic, steel and concrete pipes. The best manufacturing technique of fabricating FRP composite pipes is filament winding method. In addition to the properties of the fibre and matrix of the FRP pipes, winding angle, fibre volume and orientation/sequence are significant factors that determine the strength of the FRP filament wound composite pipes.

There are several research studies on the FRP composites. However, there is a very limited extensive review study on the raw materials used in the FRP composite pipes, production, utilisation, repair and recovery of the FRP composite pipes, as well as recent developments and innovations. Therefore, this review study has critically and extensively reported previously published articles on the lightweight FRP composite pipes to contribute to knowledge in aforementioned and neglected areas as well as proposed optimum FRP composite pipe for different areas of application in various pipeline industries.

The burst, buckling, durability and corrosion analysis of several lightweight FRP composite pipes and their applicability have been critically reviewed and reported within the scope of this paper. It was evident that external, internal and hydrostatic pressures are mainly used to analyse the burst of the composite pipes. Also, the buckling of composite pipes occurs due to energy absorption under any or combined effect of torsional, tensional and compressive loads. The pipe length, diameter and thickness, reinforcing elements, matrix and type of constraints are factors influencing the buckling behaviour of composite pipes after the torsional loading of the FRP composite pipe. Presently, comprehensive experimental investigations into the influence of torsional stress on composite pipes are rare.

Moreover, the durability properties of FRP composite pipes depend on their environmental conditions. The durability performances FRP composite pipes reduce due to the adverse effects of environmental ageing or harsh conditions: ultraviolet rays from solar energy, hot medium, chemical attack (acidic medium), among others. These are worse if the fibre is an uncoated and untreated natural plant hydrophilic reinforcement. The detrimental consequences, such as high water absorption, swelling, de-bonding, different types of corrosions, change in surface morphology, loss of aesthetics, week fibre-matrix interfacial adhesion which eventually reduces the mechanical and other structural properties of the FRP composite pipes. However, a comparative specific absorbed energy has been achieved with a low-density natural flax fibre reinforced epoxy composite pipes, which was very close to that of metal composite pipes, such as stainless steel and aluminum tubes.

Recent advances in manufacturing and application of FRP composite pipes have attracted the use of many numerical simulations through several software programmes, such as ABAQUS, ANSYS, I-DEAS, FEM, NASTRAN 2000, ADINA and among other industrial and in-house developed programmes. They are used to analyse, predict and optimise the properties of the composite pipes. Therefore, the future outlook or possibility of inventing an enhanced FRP composite pipes is very bright. Importantly, the chronologically arranged knowledge embedded inside this review paper has potential of benefiting researchers, designers, manufacturers and users of FRP composite pipes.

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Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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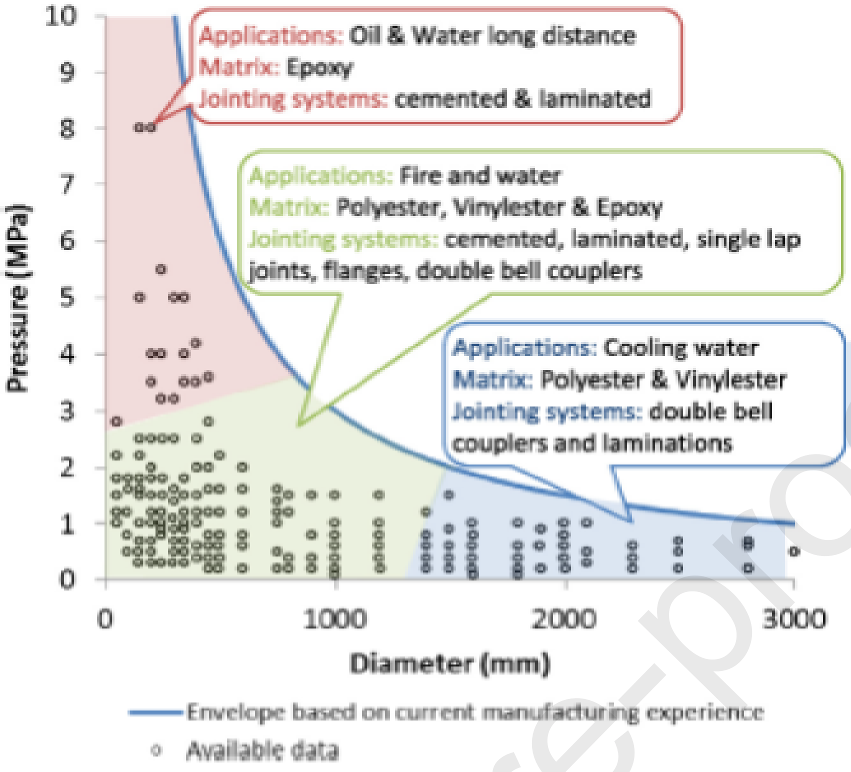


Fig. 1. Dissemination of FRP composite pipes [36].

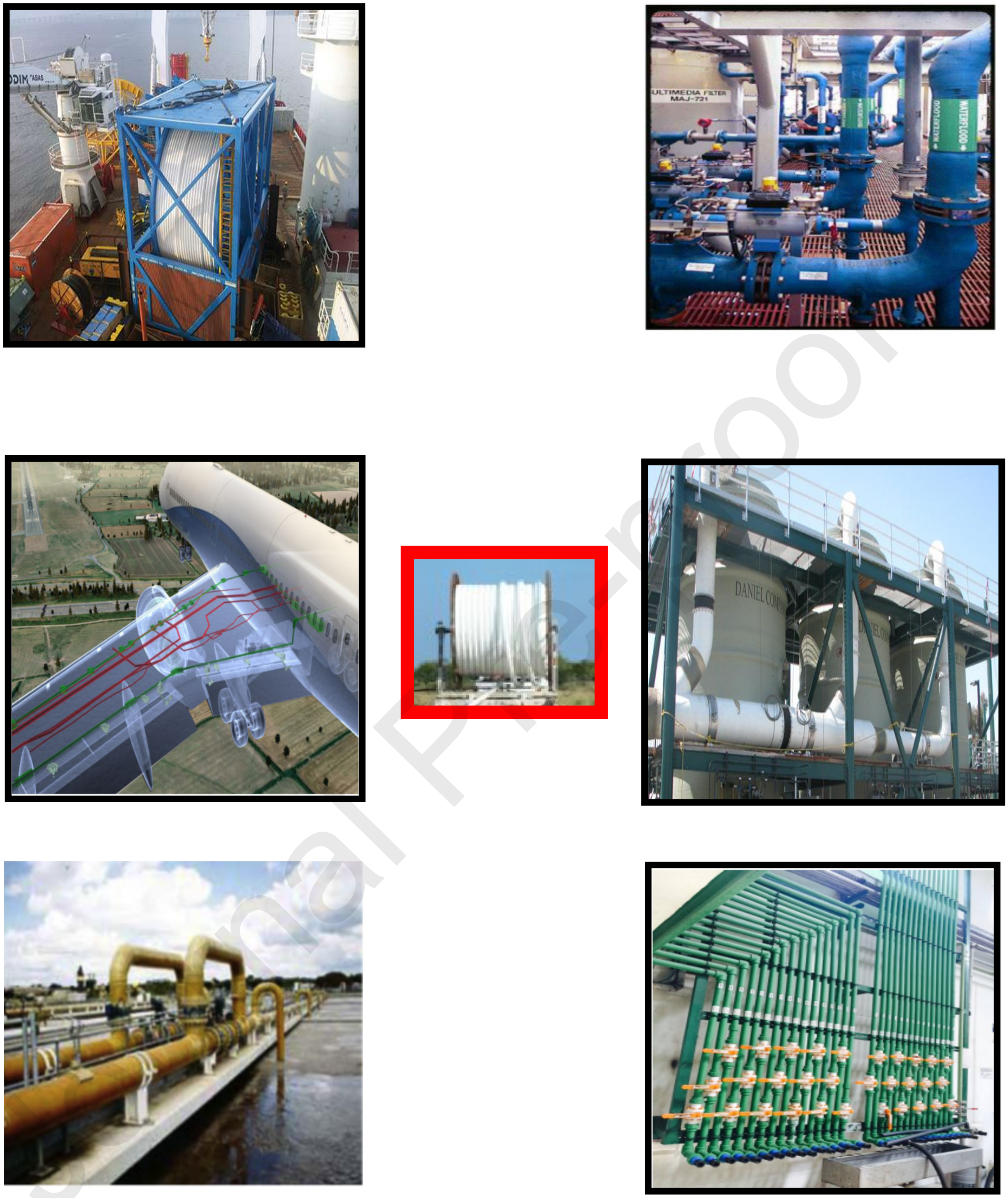


Fig. 2. Implementation of FRP composite pipes in several large scale applications.

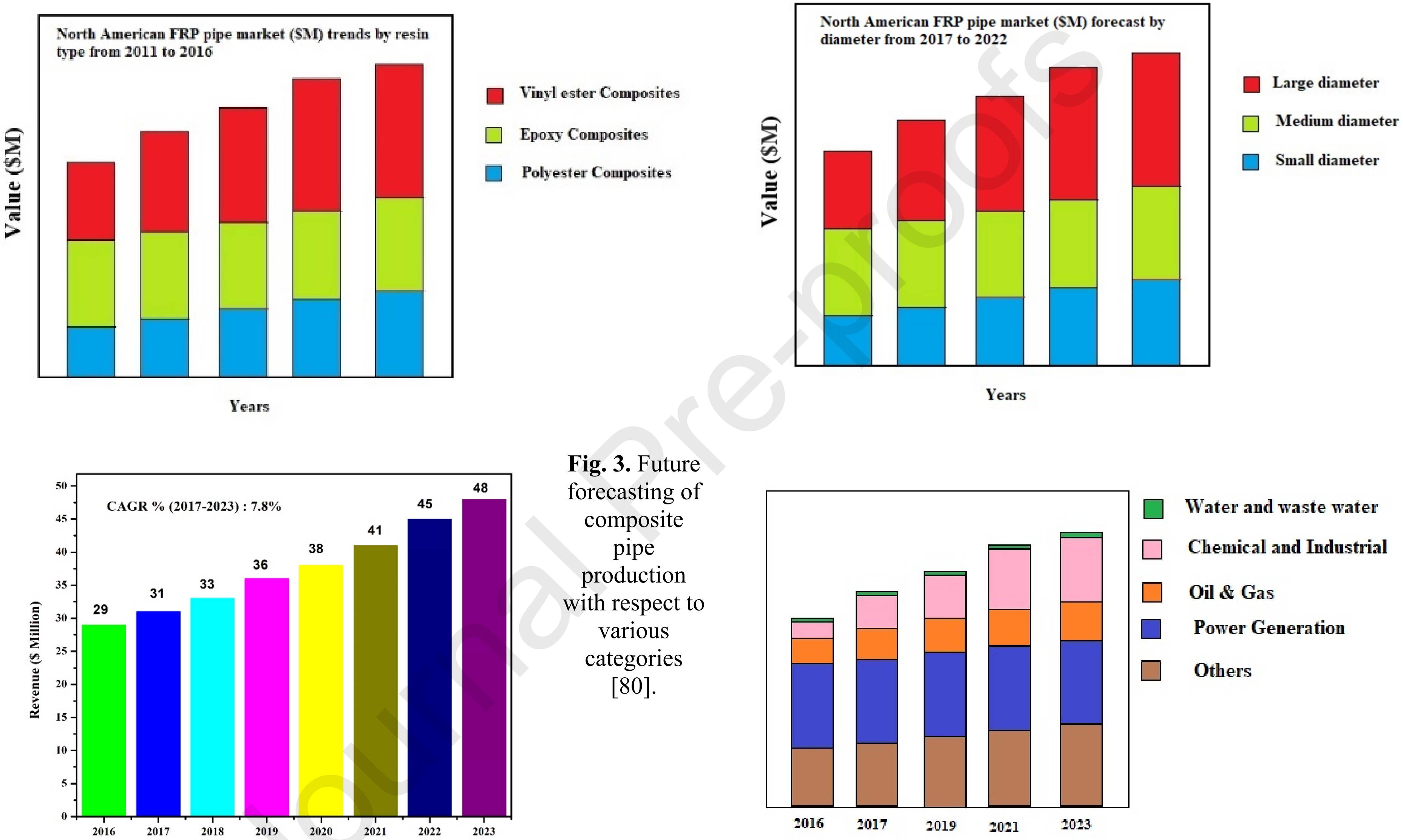


Fig. 3. Future forecasting of composite pipe production with respect to various categories [80].

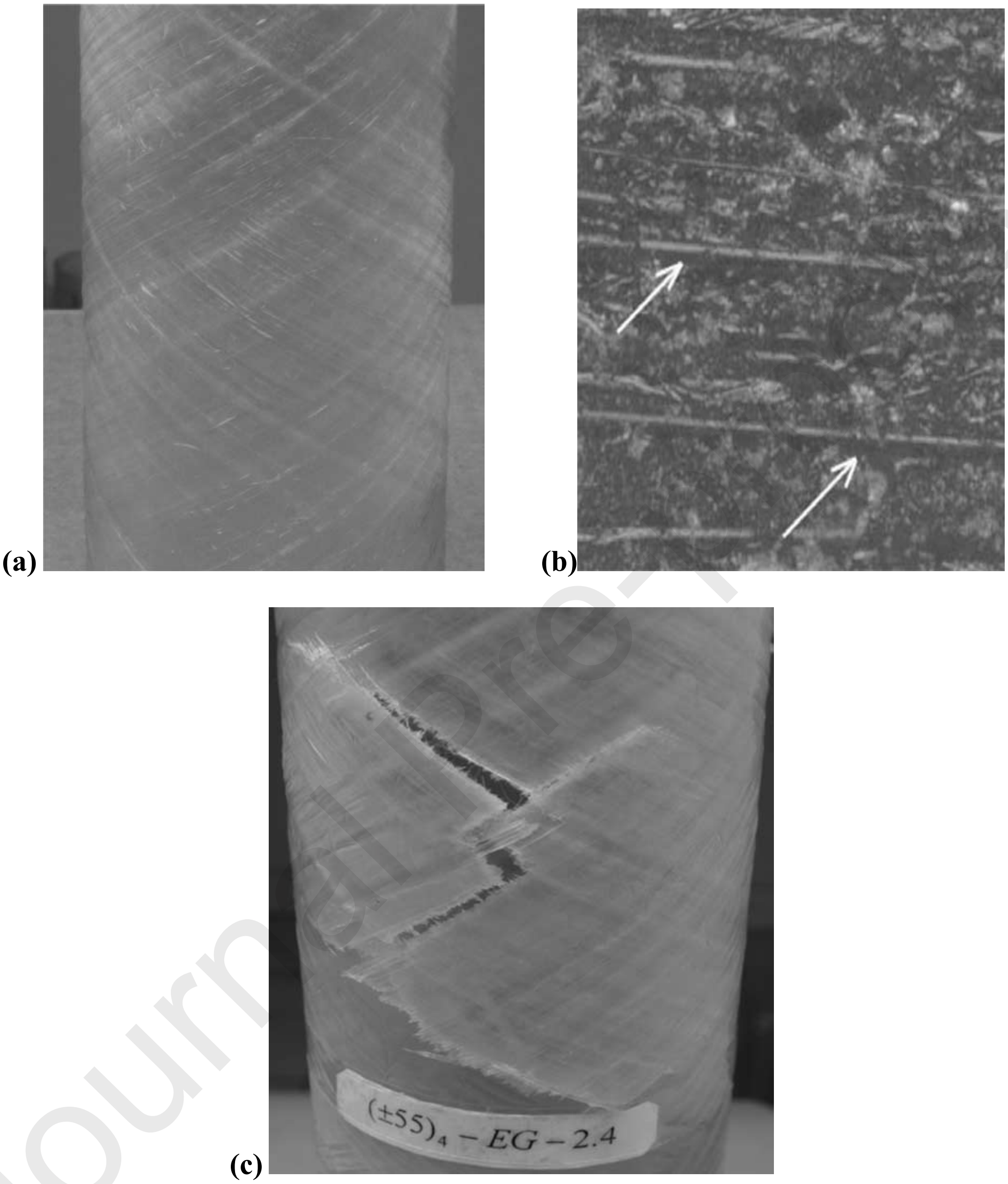
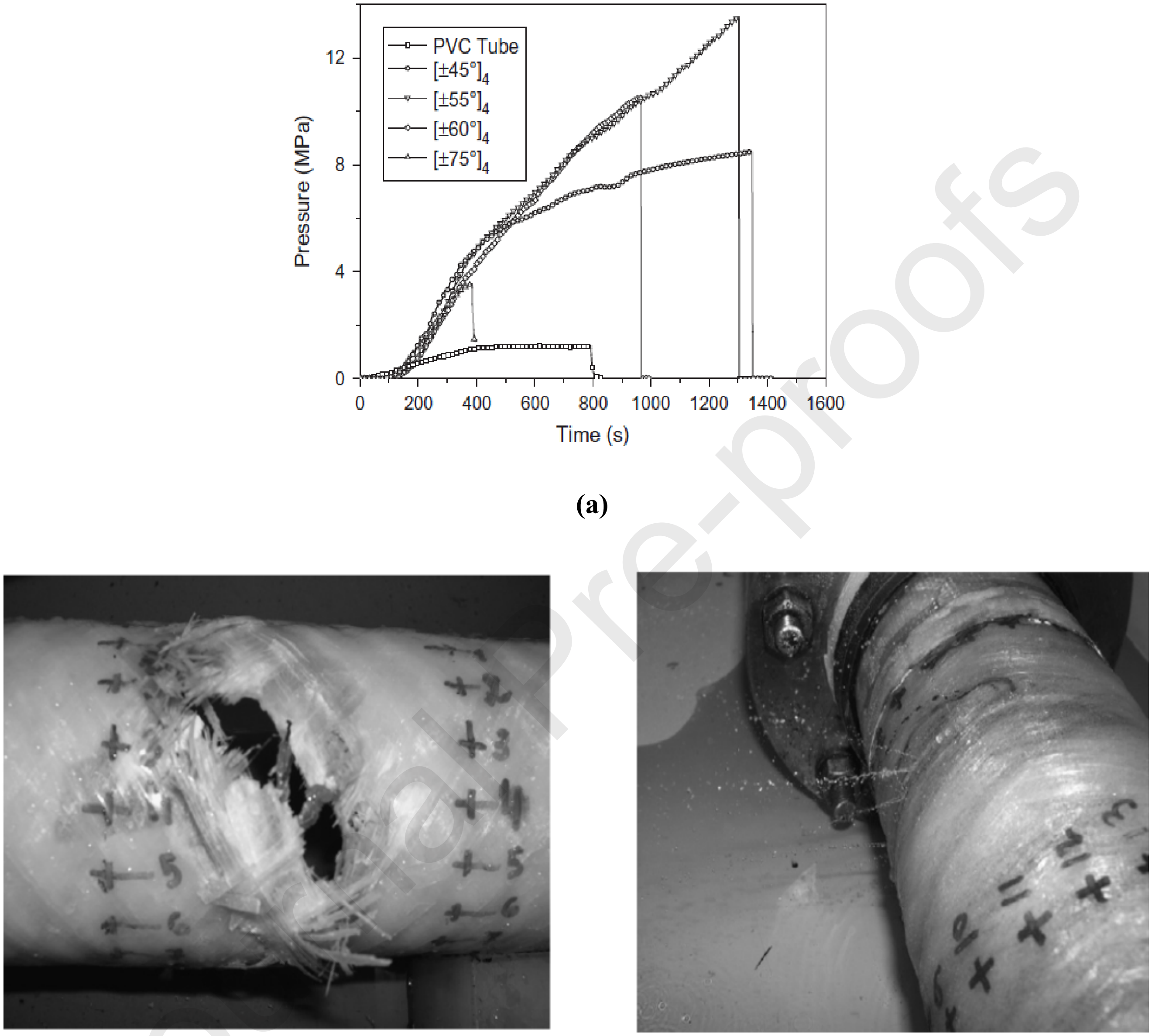


Fig. 4. Failure mechansims: (a) whitening, (b) delamination (caused by de-bonding) and (c) final fracture of E-glass/epoxy composite pipes [90].



(a)

(b) **(c)**

Fig. 5. (a)Variation of internal pressure for various winding angles with respect to time response (b) final fracture, and (c) leakage [94].

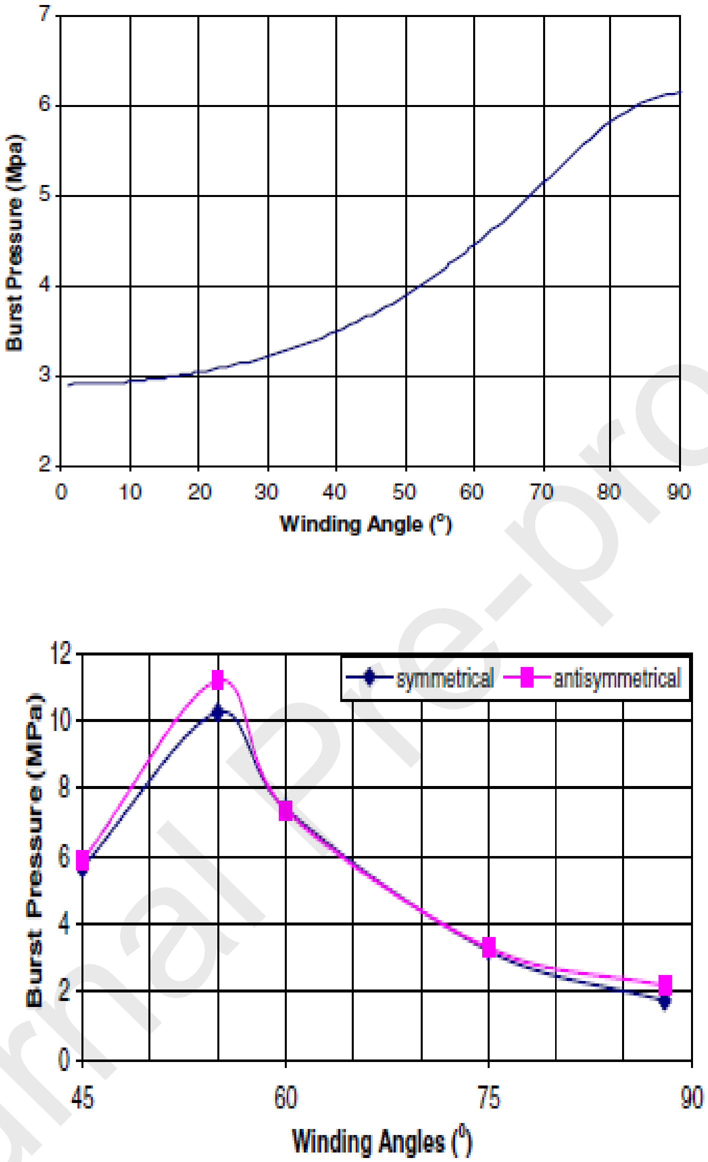


Fig. 6. Performance of burst pressure with the effect of winding angles on different lay-up sequences [95].

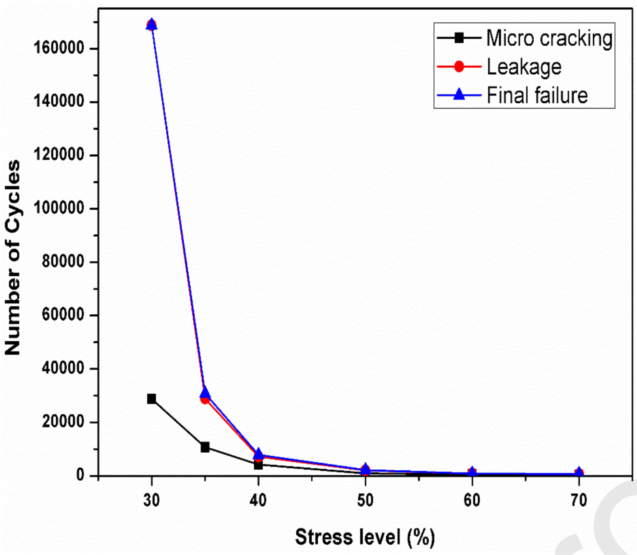


Fig. 7. Different failure mechanisms with varying stress level and number of cycles [96].

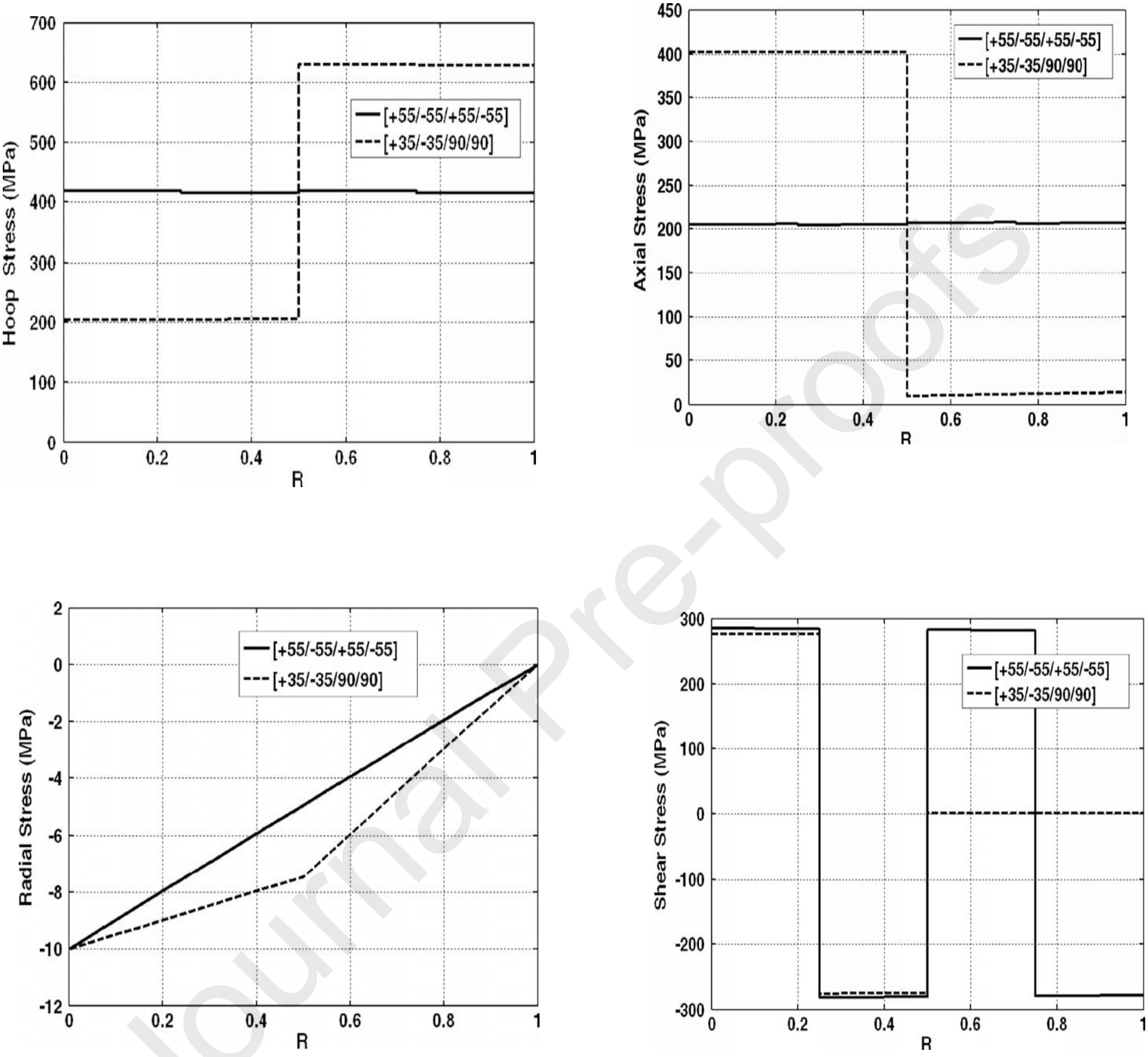


Fig. 8. Behaviour of different stress distributions (hoop, axial, radial and shear) at varying stress ratios [99].

Fig. 9. E-Glass/epoxy FRP composite pipes filled with concrete subjected to an axial loading [125].

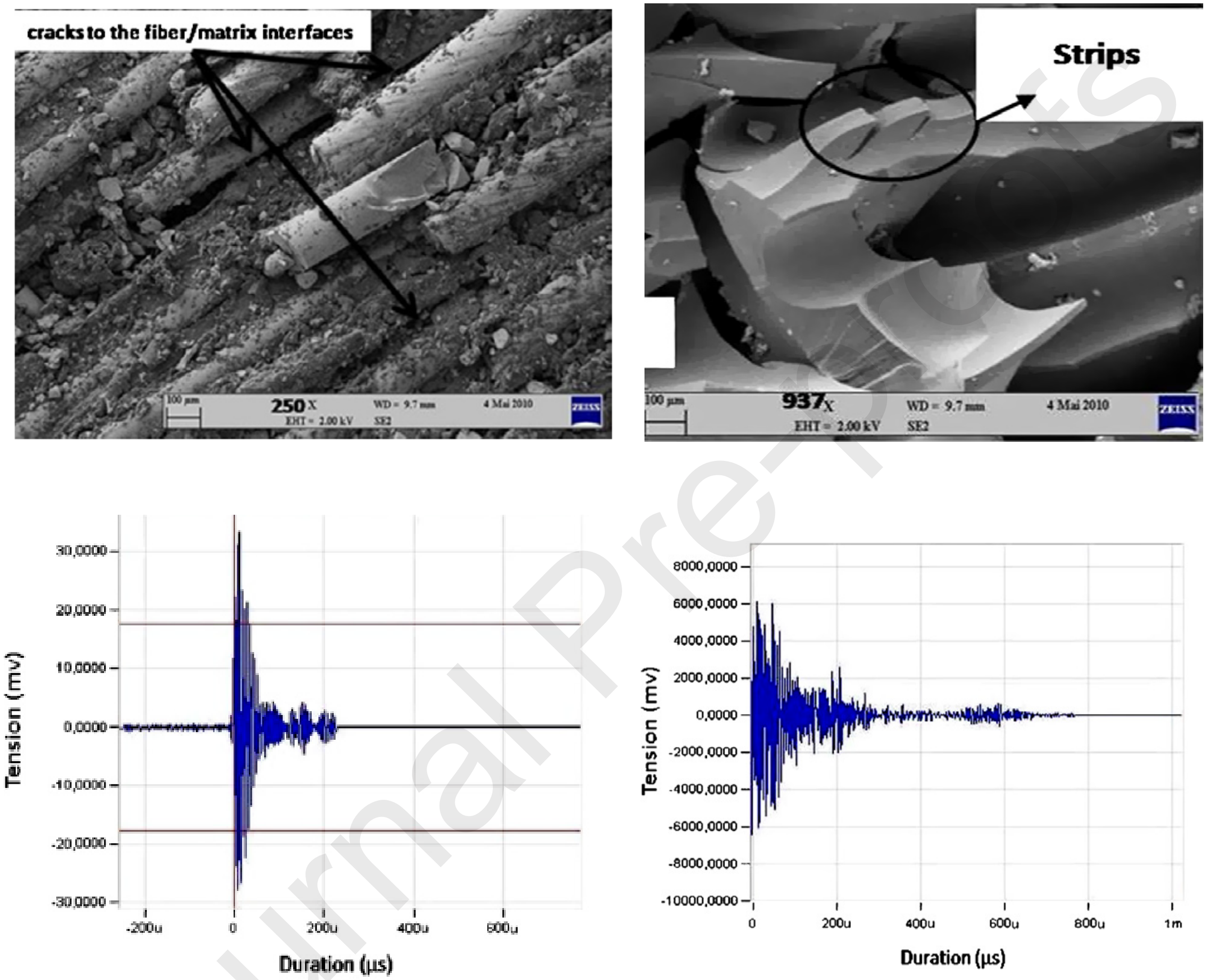


Fig. 10. Micrograph of failure mechanism and the corresponding acoustic wave forms [130].

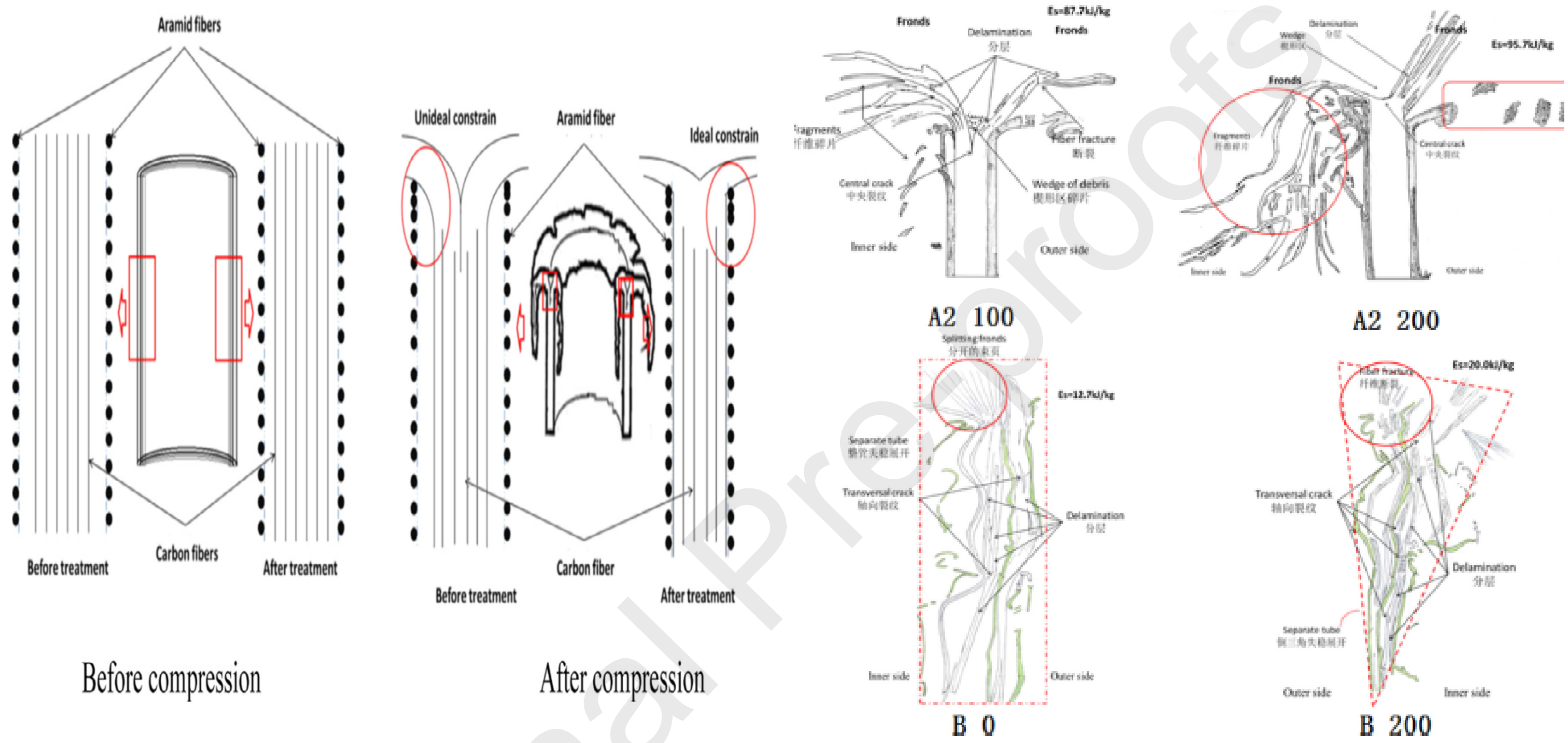


Fig. 11. A schematic diagram of energy absorption behaviour of various composites [140].

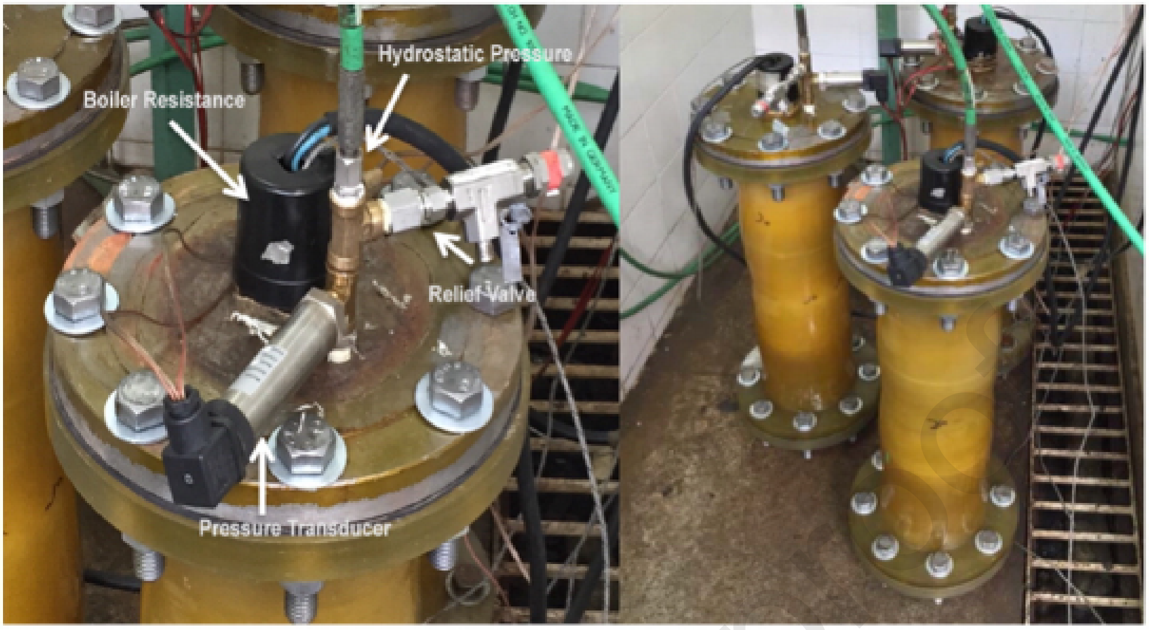


Fig. 12. Hydraulic test apparatus for prediction of burst failure pressure of FRP pipe under ageing conditions [165].

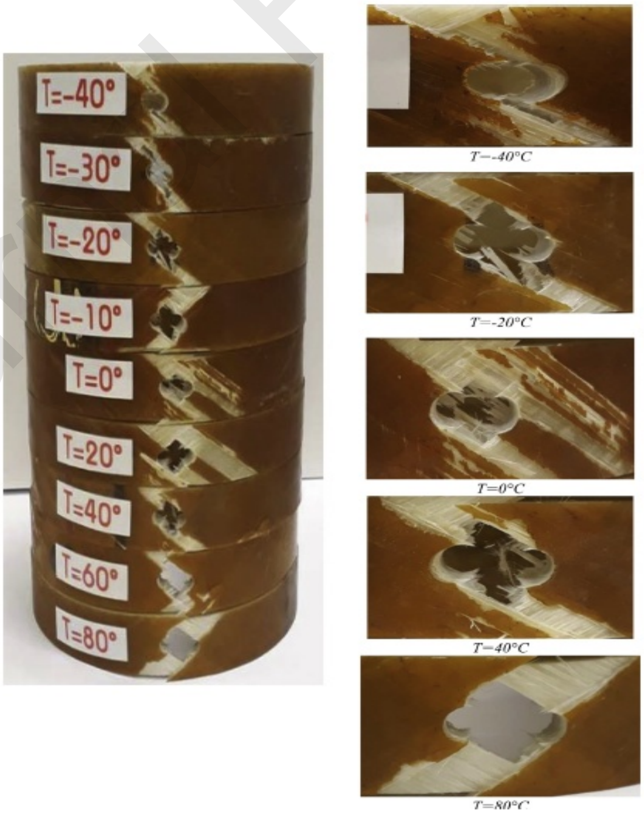


Fig. 13. Effect of thermal ageing on glass/epoxy composites pipes and its failure mechanism [159].

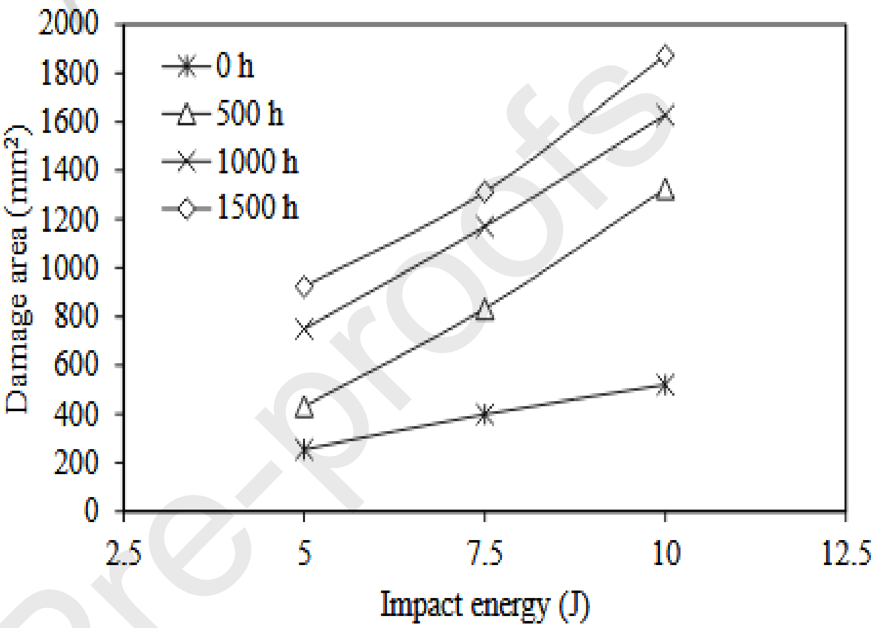


Fig. 14. Hydrothermal ageing effect on FRP pipe under impact loading [114].

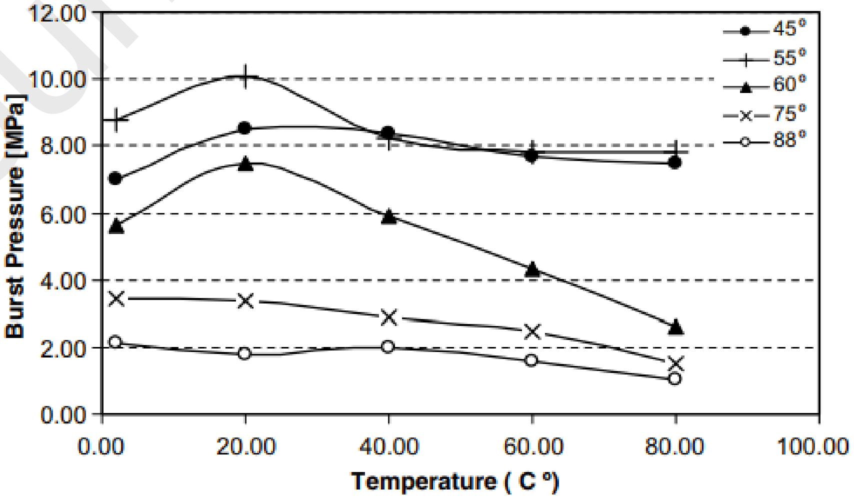


Fig. 15. Effect of temperature on burst failure [95].

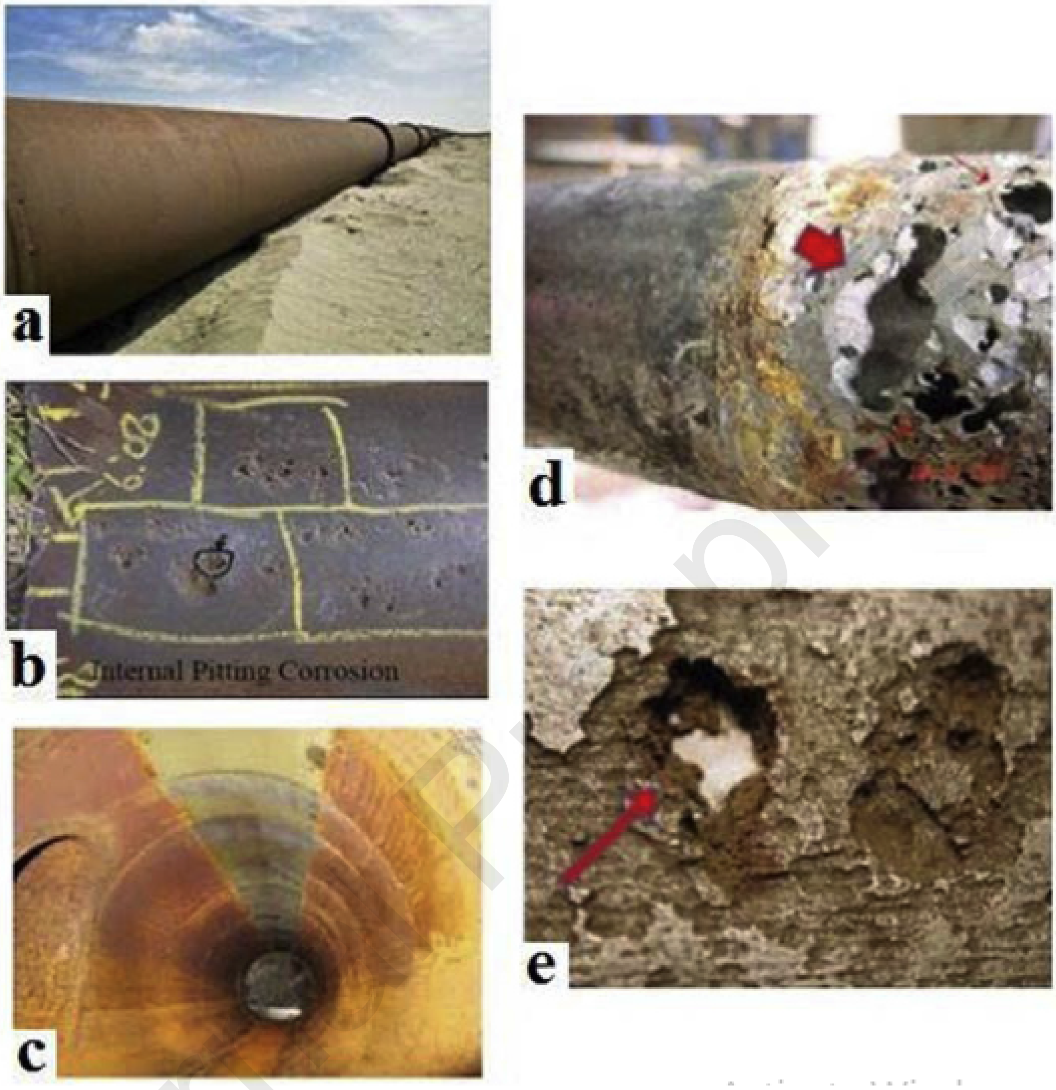


Fig. 16. (a) Uniform corrosion, (b) pitting corrosion, (c) cavitation and erosion-corrosion, (d) stray current corrosion, (e) Microbiologically-influenced corrosion [183].

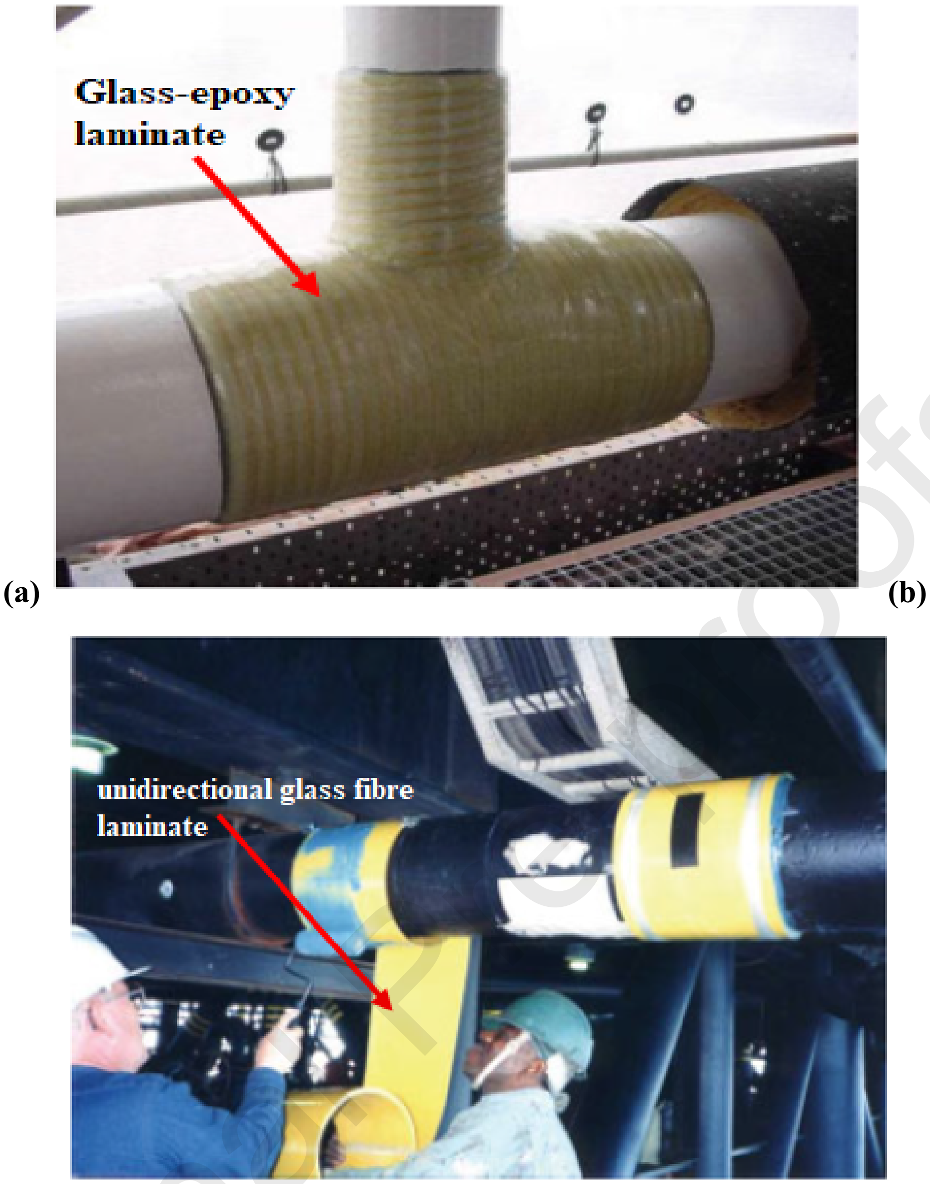


Fig.17. (a) A repaired externally corroded pipe by commercially used clock spring [148] and (b) glass/epoxy composite on 400 mm pipe [204].

Table 1 Merits, demerits and applications of manufacturing methods for the FRP composite pipe.

Type of fabrication method	Advantages	Limitations	Applications	Ref.
FWM	Maximum accommodation of volume fraction. High degree of fibre arrangements. Simplified working procedure with minimum production cost. More flexible composites design through the change in manufacturing process parameters. Repeatability of larger structures is possible.	Controlling winding angle less than 5° is difficult. Investment cost is high. Occupy more space. Require additional process of preperg formation for thermoplastic polymers. Difficult to maintain the uniform impregnate of fibre. Non-permanent mandrel. Limited surface profiles. Only produce convex shaped components.	Oil and gas transporting pipes, drive shafts, deep sea oil drill risers, storage, tanks, pressure vessels, Rocket motor cases, pipes and fittings, fuel pipes in aero industries, water pipe line supply in agricultural field.	[22-24]
CCM	Expensive steel mandrel can be eliminated.	Require additional technology to prepare thermoplastic mandrel.	Hydraulic systems with finished internal surface like cranes, CNC components and aircrafts.	[29]

Even pellet form of thermoplastic matrix can be used.	Difficult for thick wall pipes. Achieving uniform pressure is difficult.	Propeller shaft and front and axle drive shafts for automobiles and trucks.
Arrangement of chopped fibres and mat fabric does not take more time.	Time consuming process for impregnations.	
Enhanced surface quality.	No accurate winding angle Agglomeration of filament.	

Table 2 Comparsion of installation costs of FRP pipe and steel pipe for the length of 6500 feet.

Activity	Composite pipe line	Steel pipe line
Mobilisation	2-trucks	6-loads
Equipment	1 x 200 D series track hoe	2 x 250 D series track hoe
Manpower	1-supervisors	1-supervisors
	1-equipment operator	2-equipment operator
	2-laborers	2-welders
		2-weld helpers
		2-laborers
Testing	1-digital dead weight	1-digital dead weight
	2-recorders	2-recorders

X-ray	Not needed	100% needed
Risers	Cathodic protection	Only coating
Demobilisation	2 trucks	4 loads

Source: https://www.lbcg.com/media/downloads/events/503/12-00-otto-comin-flexpipe-systems.8597.pdf

Table 3 Essential characteristics of and useful information on FRP composite pipes [45].

Resins used for FRP Pipes	Required characteristics of resin	Reinforcement for FRP pipes	Required characteristics of reinforcement	Associated standards for FRP pipes	Marketting areas of FRP pipes	Necessary characteristics of FRP pipe
Polyester	General purpose resign. Better weathering resistance. Improved corrosion resistance to acids. Offshore and	E-Glass	Good mechnical strength. Improved corrosion resistance. Fibre type,	**ASTM 3262**: Reinforced –platic sewer pipe.	Water piping.	Corrosion resistance and stiffness to weight ratio.

	construction industries.		such as chopped and fabric.			
Vinyl ester	Excellent chemical, corrosion and heat resistance. Offers better fire resistance. Good resistance against caustic solution, acid , solvents and other hugh concentrated mediums.	S-Glass	Compatability with matrix. Density of fibres. Good impregination behaviour.	**ASTM 3517**: Reinforced –plastic pressure pipe.	Chemical and Construction.	Burst strength Bucklig resistance.
Epoxy	Good mechanical strength. Requires additional energy for	Carbon		**ASTM 3681**: Testing the corrosion perfroma	Oil and Gas industries.	Low instalation cost.

	curing. Improved chemical and acid resistance. Improved hydrothermal resistance.			nce of composite pipes.		
Furan	More sensitive to corcumstances Excellent resistance to solvents. Good perfroamnce against alkaline. Good design flexibility.	Aramid		**ASTM 3839**: Proper installation of composite pipes.	Power gereation.	Dimensional stability.
Thermoplastic	Ease flowbility. Lower melting temperature.	Natural fibres		**EN ISO 14692**: Reinforced compsoite pipes for	Offshore condition.	Electrical conductivity.

Impregnation behaviour with fibres. Suitability for madrel production.	Petroleum and natural gas industries .

Table 4 Geometry, testing conditions and material properties of filament wound composite pipes.

S/N	Fibre/Matrix	Outside (OD)/ Inside (ID) Diameter (mm)	Thickness (mm)	Winding angle in degree	Testing standard	Testing conditions	Hoop Tensile (T)/compressive (C)/burst (B) strengths (MPa)	Ref
1	E-glass/epoxy	150(OD)	3.64	90°	ASTM D2290	Room temp	901.15 (T)	[108]
		150(OD)	3.14	10°	ASTM D2290	Room temp	27.45 (T)	
		150(OD)	3.14	45°	ASTM D2290	Room temp	277.3 (T)	
2	E- glass/epoxy	100(OD)	2.5	45°	ASTM D695-10	Axial compression with room temp	118.91 ± 10.50 (C)	[195]
		100(OD)	2.5			Axial	69.17 ± 8.40	

				55°	ASTM D695-10	compression with room temp	(C)	
		100(OD)	2.5	63°	ASTM D695-10	Axial compression with room temp	59.38 ± 6.50 (C)	
3	Glass/vinylester	305(OD)	7.5	---	---	Room temp	303.6 ± 0.03 (T)	[129]
4	Glass /epoxy	90(OD)	10	$\pm 45^o$	ASTM: D2290	Room temp	156.33 MPa (T)	[257]
5	E- glass/epoxy	200(OD)	7.9	±55°	ASTM D2290	Room temp	220.26 (T)	[37]
6	E- glass/epoxy	200(OD)	7.29	±55°	---	Axial compression and room temp	143.15(C)	
7	E-glass/polyester	71.10(OD)	3.45	$[90^0/(\pm 61^0)_2]_s$	---	Room temp	49.13 ± 1.54 (B)	[258][259]
8	E-glass/polyester	67.60(OD)	1.70	$[90^0/\pm 61^0]_s$	---	Room temp	22.34 ± 0.90 (B)	[259]
9	Glass/epoxy	86.0 ± 0.2 (ID)	6.2	±55°	ASTM D2290	-20^o temperature	255 (T)	[159]
						-40^o temperature	340 (T)	
						0^o temperature	215 (T)	
						20^o temperature	223 (T)	
						40^o temperature	192 (T)	
						60^o temperature	148 (T)	
10	Carbon/epoxy	72 (ID)	3	$\pm 55^o$	ASTM D2290-	Room temp	410 (B)	[260]

					12		377 (T)	
11	Basalt /Epoxy Composite Tube	20 (OD)	1.58	±30º	ASTM D2290	Room temp	727 (T)	[261]
	Glass / Epoxy Composite Tube		2.58	±30º	ASTM D2290	Room temp	501 (T)	
12	Glass/ epoxy	106 (ID)	3.1	±60º	---	Room temp	188.226 (B) 30.99 (T) 64.19 (C)	[262]
				±45º		Room temp	226.837 (B) 72.44 (T) 61.15 (C)	
	Basalt/epoxy	106 (ID)	3.1	±60º	---	Room temp	186.487 (B) 40.08 (T) 76.97 (C)	
				±45º		Room temp	227.526 (B) 42.37 (T) 70.57 (C)	
	Glass/basalt/ epoxy hybrid combination.	106 (ID)	3.1	±60º	---	Room temp	201.326 (B) 29.76 (T) 55.13 (C)	
				±45º		Room temp	239.937 (B) 39.68 (T) 56.01 (C)	

Table 5 Various ageing conditions of FRP pipe and their failure conditions.

Type of materials	Type of ageing	Max duration	Details	Type of study/ ASTM Standards	Degradation behaviour	Observations	Ref
E-glass/ vinylester	Sea water	185 days	• Immersing sea water and tap water temperature was 25 ^{o}C • In addition, the lower temperature 2 ^{o}C with normal water was also used for conditioning.	Buckling strength (ASTM D5229)	≈59.70%	• More moisture absorption was noted on tap water condition. • Mechanical strength and bonding were more weakened at high temperature immersion condition.	[148]
E-glass/ vinylester	Tap water	212 days			≈64.18%		
Glass/epoxy	Hydro thermal	1500 hrs	• Pipes were hydrothermally aged under hot water with 80 ^{o}C for a period of 500, 1000 and 1500 hrs.	Compression strength (ASTM D695-10)	≈34.60%	• The degradation of bonding between fibre and matrix was observed, due to moisture intake. • More	[195]

			• The compressive test was performed with various temperatures of 45 ^{o}C and 65 ^{o}C.			strength reduction on 1500 hrs condition.	
Glass/epoxy	Hydro thermal	1500 hrs	• The FRP pipe were manufactured with winding angle of 55^{o} and immersed in hot water temperature of 80 ^{o}C with time interval of 500, 1000 & 1500 hrs	Low velocity impact strength (ASTM D2444)	Increased	• At 1500 hrs aged, FRP pipes absorbed less energy. • Energy absorption in all aged pipes (except 1500 hrs) was a little higher than unaged pipes, due to plasticisation of materials.	[114]
				Burst strength (ASTM D1599)	≈30.00%		
Glass/epoxy	Seawater	12 months	• The FRP pipe was manufactured with various diameters of 50, 75, 100 and 150 mm. • All the pipes were immersed in sea water for	Low velocity impact strength	Increased	• Larger failure area was observed in a smaller diameter pipe. • Energy absorption of the pipes was decreased with an	[140]

			3, 6, 9 and 12 months. • All the aged pipes were tested with impact loads of 15, 20 and 25 J.			increasing pipe diameter.	
Kevlar/ HDPE	Hydrostatic pressure test	10000 hrs	• The pipe was immersed in hot water temperature of 65 °C and subjected to pressurised water of 15 MPa; was passed inside the set of pipes for 10000 hrs. • During test pressure-time at failure stage data was collected to predict the pipe life.	Monotonic internal pressure (ASTM D2992)	40.45%	• Observed decrease of pressure resistance in long-term performance compared to the initial state of the pipe. • Found number of undamaged pipe as 3 for above 10000 hrs ageing and damaged pipe as 10 for below 1000 hrs ageing.	[175]

Table 6 Types of elements and parameters considered for numerical analysis, using various software packages.

Material	Program/Code	Mesh	Study parameters	Ref
Glass/epoxy	Elastic FEM Program	Shell element	Inter-laminar shear stress and strain	[256]
Fibre glass RP	SSTIPN	Non-linear	Buried soil box	[229]
E-glass/epoxy	Elastic FEM Program	Orthotropic, shell element	Axial compressive load and axial tensile	[228]
GRP pipe	Program FORTRAN77	Axisymmetric shell, non-linear	axial compression buckling	[230]
GFRP/polyester	ABAQUS	8 node plain strain element	Crack propagation	[231]
Glass/vinyl ester	MARC Code	3D, 8 node brick element	Deformation, crushing mechanism and energy absorption	[232]
E-glass/epoxy/VE	COSMOS	Eight-note composite	Internal pressure test and interfacial stress	[233]
GFRP/PVC	ABAQUS F E	Isoparametric shell elements	Shear stress and peel stress	[234]
GFRP/epoxy	ABAQUS 6.2	hexahedral solid elements, solid/shell	Damage modelling	[235]
Glass/epoxy	ANSYSL	PLANE55 axial symmetry element	Curing time	[237]
Glass/epoxy	ANSYS	SHELL 281 element	Natural frequency	[238]
Glass/epoxy	ABAQUS 6.11	cohesive element COH3D8,	Impact simulation	[236]
Glass/epoxy	ANSYS	20 node isoperimetric quadrangular elements	Stress and failure	[239]
Carbon FRPP	CASTEM 2000	3D-thin shell element	Bi-axial stress	[241]
CFRPP	MARC	Isoperimetric-8 node axis-	Shear stress and fatigue	[243]

		symmetric element.		
Carbon pipe	C Program	8 node brick element	Impact damage and dynamic behaviour	[245]
Carbon/epoxy	ANSYS / I-DEAS	3D-brick solid 46	Thermal deformation	[246]
FLEXTREME/carbon	ANSYS	2D axisymmetric	Contact pressure	[247]
Carbon/epoxy	ANSYS	3D, 8 node element	Damage evaluation and cracking	[248]
Carbon/glass	ANSYS/ANN	3D-shell element	Absorbed energy	[253]
Graphite/epoxy	FEM Code	3D, 8 node solid brick element	Stress analysis	[252]
Graphite	Elastic FEM Program	3D-shell element	Stress distribution	[249]
Graphite/epoxy	FEM code	32 DOF shell	Impact behaviour	[250]
Graphite/epoxy	ANSYS	Isotropic, SOLID 95	Shear stress, displacement	[251]
Embankments	LSBUILD	Isotropic condition	stress-strain behaviour	[217]
Composite pipes	CANDE,ADINA	4 node quadrilateral	stress-strain behaviour	[225]
Boiler FRPP	FEM Code	2D plane strain element	Hydrostatic pressure	[226]
Laminate model	ABAQUS	6 node triangular shell	Impact force, displacement	[254]