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# **Analysis of failure pressure of defective pipes repaired with composite systems considering the plastic deformation of pipe**

## **Abstract**

Wrapping a composite material around the wall loss defective pipe is a well-known practice in pipeline rehabilitation as per guidelines provided by the design standards ISO/TS 24817 and ASME PCC-2. This work presents an analytical model to evaluate the composite repair thickness for a damaged pipeline with accounting for the plastic deformation and compare it with the results of design codes and numerical models. Hydrostatic tests performed on a repaired pipe using a composite system in different laboratories were used to validate the repair thickness using different criteria. The results show that the proposed analytical model is in good agreement with the numerical models and experimental results. The repair thickness calculated using the design codes (ISO/TS 24817 and ASME PCC-2) is more conservative, which results in repaired pipes failing outside the defect section. However, the proposed model predicts a lower composite thickness to sustain the same design pressure which enables the saving composite material. The proposed model can be refined further by accounting for the composite laminate strain using the Tsai-Hill or Hashin failure theory instead of allowable strain.

**Keywords:** Composite repair thickness; Analytical modelling; Plastic deformation; Corroded pipelines; Composite materials.

## **1. Introduction**

The repair of corroded/damaged pipelines with fiber-reinforced polymer composite materials is a well-developed practice in many industries over the conventional repair methods. Metallic pipeline repairs made with FRP materials offer many benefits which include: lightweight, high strength and stiffness, corrosion prevention, quick repair, safety and cost effective process [1-4]. Besides these advantages, still several issues need to be focused in detail for better performance of the composite repair system. These issues include: design pressure, delamination between the metal pipe and composite sleeve, effect of the infill (putty) material, composite repair thickness and analytical modelling [5-8].

Complete guidelines of the composite repair system of damaged pipelines are well described through the ISO/TS 24817 and ASME PCC-2 standards [9, 10]. Many researchers investigated the performance of composite repair system with respect to material (composite material, adhesive and putty) and geometrical (pipe defect geometry,

sleeve repair thickness, fiber orientation) parameters of the repaired system through experimental (hydrostatic tests) and numerical analysis [11-15]. Many researchers have been working to improve and modify the design codes over the selection of composite materials and design factors such as design pressure and composite repair thickness for a better performance of the composite repair system of corroded pipelines [16-19]. Composite repair thickness is one of the most important repair design parameters and a conservative thickness is necessary for safe repair design.

Using ISO/TS 24817 standard a high conservative composite repair thickness is calculated, as it does not allow for pipe yielding. However, the same design standard gives a different trend of composite repair thickness for the cases in which the live pressure and wall loss defects are larger [6]. The ASME PCC-2 standard allows pipe yielding which leads to a less conservative value of composite repair thickness. The composite repair thickness obtained by the finite element model is lower than the predicted repair thickness using the ISO/TS 24817 and ASME PCC-2 standards for the same design pressure level [6, 18-21]. For example, the minimum repair thickness was found to be 5.09 mm, 4.57 mm as per the ISO/TS 24817 and ASME PCC-2 standards, respectively and 3.1 mm obtained by finite element method for the wall loss defective pipeline reinforced with a carbon composite repair system [20].

In most of the cases the predicted composite repair thickness using both the standards (ISO TS 24817, ASME PCC-2) is always higher than the finite element model for the same pressure level of composite repair system. The possible causes for over-predicting repair thickness are: neglecting of strain hardening of the pipe, neglecting axial and radial stresses as well as neglecting the presence of putty material [6, 18-21]. The prediction of a high conservative thickness using the standards (ISO/TS 24817 and ASME PCC-2) could prevent yielding/plastic deformation of the pipe at the defect region but does not ensure about the plastic deformation of the pipe at the unrepaired section. Budhe et al. [16] reported that a conservative composite repair thickness prevents failure of the pipe at the defect region, however plastic deformation occurs quite away from defect region. Contrary to the conservative composite wrap thickness, the same standards (ISO/TS 24817) predict an inadequate (less conservative) composite repair thickness for the critical wall loss (70% to 80%) defect pipe repair at failure pressure (designed pressure) [22]. Duell et al. [20] proposed a more conservative design pressure using the ASME B31.4 criterion, however, this pressure should be higher than the burst pressure of a corroded pipeline. There are well defined standards such as the ASME B31G, RSTRENG and DNV which are widely used to define the theoretical burst pressure [23].

In the present paper an analytical model is proposed to determine an accurate composite repair thickness by accounting for the plastic deformation (strain hardening) of the pipe. The proposed analytical model results were validated with the numerical model and the design standard codes (ISO/TS 24817 and ASME PCC-2).

## 2. Analytical methods

ISO/TS 24817 and ASME PCC-2 standards formulate the equation for minimum repair thickness when the pipe is subjected to internal design pressure and live pressure [9, 10]. It is assumed that the damaged/corroded pipe to be repaired has a thin wall of thickness ' $t$ ' (radius to thickness ratio is more than 10) and subjected to internal pressure ' $P_i$ '. Fig. 1 shows the wall loss defective pipe with remaining thickness ' $t_s$ ' repaired with the composite material having composite sleeve thickness ' $t_c$ '.

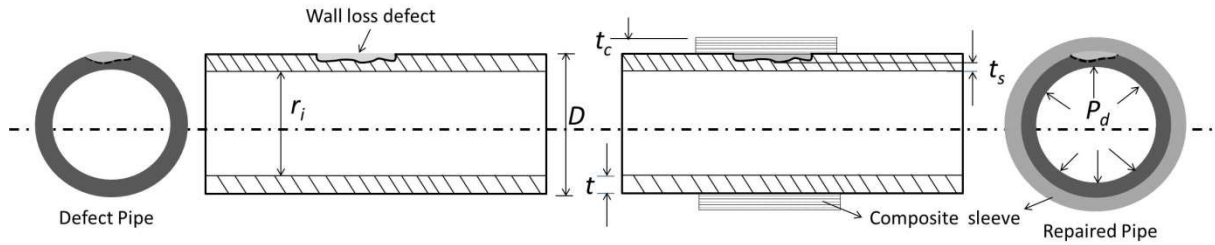


Fig.1. Wall loss defect pipeline repaired with composite sleeve.

In this section, the analytical model for determining the composite repair thickness of wall loss defective pipe with and without accounting for pipe yield behaviour is summarized and a new analytical model with accounting for plastic deformation (strain hardening) behaviour of the pipe is proposed.

### 2.1 Elastic behaviour of pipe and composite material

The behaviour of a steel pipe and composite material is idealized as linear elastic only, so the pipe can sustain pressure up to yield stress ( $\sigma_y$ ). The repair of a corroded/damaged pipe using a composite sleeve can be carried out in working condition and needs to account for the fluid pressure inside the pipe in the analysis.

The pressure of the fluid inside the pipe termed as live pressure and denoted as a  $P_{live}$  and this live pressure generates circumferential stress even without subjecting internal design pressure.

$$\text{Circumferential stress, } \sigma_c = \frac{P_{live}D}{2t_s} \quad (1)$$

$$\text{As we know, in elastic limit, } \sigma_c = \varepsilon_{slive}E_s \quad (2)$$

The strain in the pipe wall,  $\varepsilon_{slive}$  can be calculated by equating Eq. (1) and Eq. (2)

$$\varepsilon_{slive} = \frac{P_{live}D}{2t_sE_s} \quad (3)$$

The repair is then carried out and the internal pressure is gradually increased to a pressure value higher than the fluid pressure but smaller than the pressure at which the yield of steel starts to occur.

It is assumed that the radial displacement of the contact surface between the pipe cylinder and composite repair cylinder is the same, and neglecting the variation of the wall thickness due to the pressure. This can lead to the strain in the steel pipe becoming equal to the strain in the composite laminate due to the applied pressure ( $P_y$ ).

$\varepsilon_{ys}$  is the yield strain of the steel pipe and  $\varepsilon_{yc}$  is the strain in the composites when the steel reaches  $\varepsilon_{ys}$ .

Therefore, from the strain compatibility condition,

$$\varepsilon_{ys} - \varepsilon_{live} = \varepsilon_{yc} \quad (4)$$

The inside fluid pressure of the pipe is zero ( $P_{live} = 0$ ) when the production process is halted during pipeline repair, which turns the above equation:

$$\varepsilon_{ys} = \varepsilon_{yc} \quad (5)$$

From the force equilibrium equation, the total pressure exerted ( $P_y$ ) on the repaired pipe is shared by the defect pipe and the composite laminate.

Total force exerted on the repaired pipe = forced shared by defective pipe and composite laminate is:

$$\frac{P_y D}{2} = \sigma_{ys} t_s + \sigma_{yc} t_c \quad (6)$$

It is known, from eq. (5)  $\varepsilon_{ys} = \varepsilon_{yc}$ , Thus, the above equation leads to

$$\frac{P_y D}{2} = \varepsilon_{ys} (E_s t_s + E_c t_c) \quad (7)$$

The circumferential stress for a pipe under the elastic region is:

$$\sigma_y = \frac{P_y D}{2t_s} = E_s \varepsilon_{ys} \quad (8)$$

It can be noted that eq. (7) can be rearranged using Eq. (8) to give pressure exerted on the repaired pipe ( $P_y$ ):

$$P_y = \frac{2 \sigma_y (E_s t_s + E_c t_c)}{D E_s} \quad (9)$$

Now, the composite repair thickness can be calculated for the design pressure using the allowable pipe and composite material properties for safe repair design.

$P_y$  is substituted by the design pressure  $P$  based on criteria (ASME B 31.4, ISO/TS 24817, etc.)

$\sigma_y$  is substituted by lower yield stress of pipe

$t_c$  is the design composite thickness or minimum composite repair thickness

$$t_c = \frac{PDE_s}{2E_c\sigma_y} - \frac{E_s t_s}{E_c} \quad (10)$$

Equation (10) can be used to calculate the composite repair thickness ( $t_c$ ) provided that the steel pipe isn't allowed to yield, which leads to a higher conservative composite sleeve thickness. This higher composite sleeve thickness demands for more composite material which imposes a higher repair cost. However, this can apply where the more critical operating condition will be experienced by the repaired pipe.

## 2.2 Elastic-perfectly plastic behaviour of pipe and elastic behaviour of composite

An increase in the internal pressure towards the ultimate pressure which is higher than the yield pressure will not be sustained by the steel pipe, as it is idealized as elastic-perfectly (ideally) plastic. The additional pressure over the yield pressure is only sustained by the composite laminate material as the pipe can no longer resist any higher pressure above yield, as it assumes  $\sigma_y$  (yield stress of the pipe) is the maximum stress, even allowing for increments in strain, which is the assumed case.

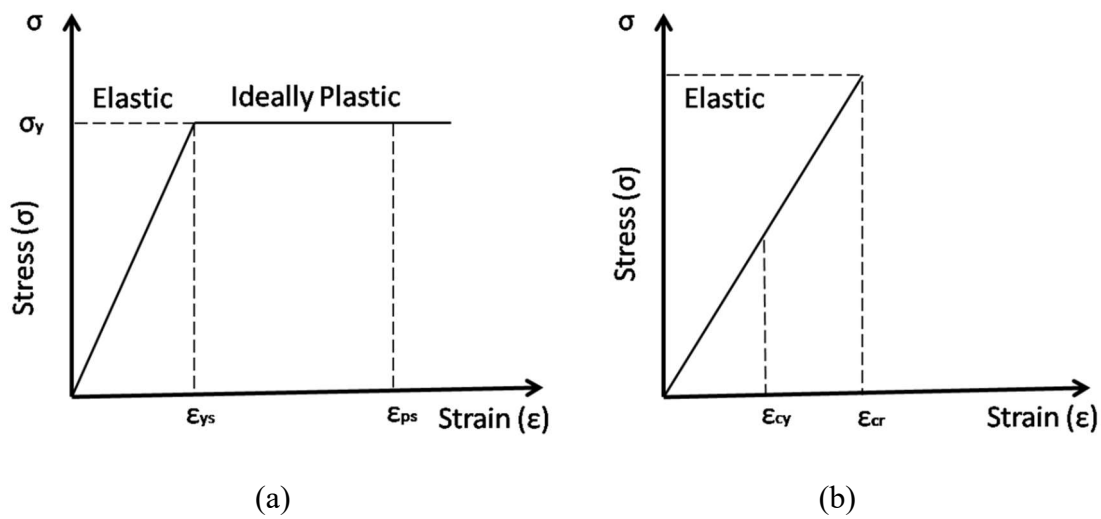


Fig.2. Idealized stress- strain curves of (a) steel material is elastic-perfectly plastic (b) composite material is elastic only.

The strain increases in the steel pipe without increasing in stress of the pipe is due to the force imposed by the composite only.

The strain compatibility between the steel pipe and composite laminate is as (Fig.2);

$$\varepsilon_{ps} - \varepsilon_{ys} = \varepsilon_{cr} - \varepsilon_{cy} \quad (11)$$

From the force equilibrium equation, the total pressure exerted ( $P_u$ ) on the repaired pipe is shared by the defective pipe limited up to the yield strength and later only shared by the composite laminate.

Total force exerted on repair pipe = forced shared by defective pipe and composite laminate

$$\frac{P_u D}{2} = \sigma_{ys} t_s + \sigma_c t_c \quad (12)$$

The stress in the composite laminate is,  $\sigma_c = E_c \varepsilon_{cr}$ , thus the above equation leads to

$$\frac{P_u D}{2} = (\sigma_{ys} t_s + E_c \varepsilon_{cr} t_c) \quad (13)$$

This equation can also be rearranged in a different form to provide the ultimate pressure  $P_u$  as

$$P_u = \frac{2E_c \varepsilon_{cr} t_c + 2\sigma_{ys} t_s}{D} \quad (14)$$

The composite repair thickness can be calculated for the design pressure using the allowable pipe and composite material properties for safe repair design.

$P_u$  is to be substituted by design pressure  $P$  of the repaired pipe that should sustain without failure and it determine based on criteria such as such as ASME B31.4, ISO TS 24817, etc [9, 24]. In the next section, the design pressure of a repaired pipe is discussed in more details.

$\varepsilon_{cr}$  is to be substituted by  $\varepsilon_c$  which is the allowable strain for the composite (depends on the expected repair life).

$\sigma_{ys}$  is to be substituted by  $S$  (which is the Specific minimum yield stress of steel)

$t_c$  is the design composite thickness or minimum composite repair thickness.

The equation (14) can be rearranged and the composite repair thickness is given as:

$$t_{min} = \frac{PD}{2E_c \varepsilon_c} - \frac{\sigma_{ys} t_s}{E_c \varepsilon_c} \quad (15)$$

Instead of the allowable strain of composite laminate  $\varepsilon_c$ , the strength of composite sleeve ( $S_c$ ) can also be used:

$$t_{min} = \frac{PD}{2S_c} - \frac{\sigma_{ys} t_s}{E_c \varepsilon_c} \quad (16)$$

The equations (15-16) are used to determine the composite thickness using ASME PCC-2 design codes in which the pipe is allowed to yield. However, pipe won't allow yielding in the ISO/TS 24817 design standard; hence the pipe strength is assumed to be lower than the yield stress of pipe. The minimum composite thickness using the design code ISO/TS 24817 code, is given as:

$$t_{min} = \frac{PD}{2E_c \varepsilon_c} - \frac{0.72 \sigma_{ys} t_s}{E_c \varepsilon_c} \quad (17)$$

Instead of the allowable strain of composite laminate  $\varepsilon_{cr}$ , the strength of composite sleeve ( $S_c$ ) can also be used.

$$t_{min} = \frac{PD}{2S_c} - \frac{0.72 \sigma_{ys} t_s}{E_c \varepsilon_c} \quad (18)$$

The equations (15-18) are widely used to determine the composite repair thickness in the oil and gas industry, as these equations give a more conservative thickness which is good for safe repair design. However, more conservative repair thickness requires more composite material to wrap the defective pipe, which is not economical.

### 2.3 Elastic-plastic deformation (strain hardening) behaviour of pipe and elastic behaviour of composite

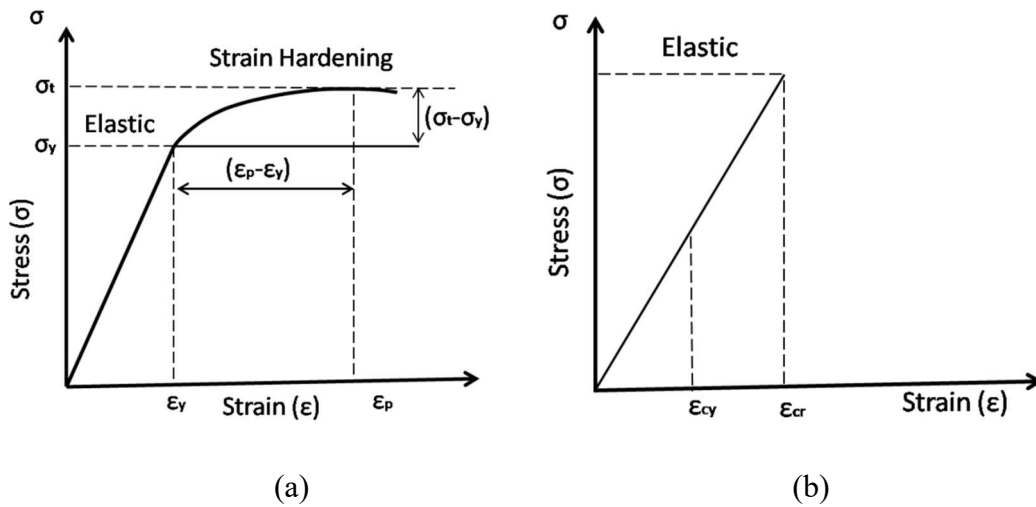


Fig.3. Idealised stress- strain curve of (a) steel material is elastic-plastic deformation (strain hardening) (b) composite material is elastic only.

With increasing internal pressure after attaining the yield pressure, the steel pipe can still sustain the design pressure as the steel pipe allows for plastic deformation (strain hardening) but is limited to the plastic deformation capacity (Fig. 3).

From the force equilibrium equation:

Total force exerted on repaired pipe = force shared by defect pipe and composite laminate

$$\frac{P_{max}D}{2} = \sigma_t t_s + \sigma_c t_c \quad (19)$$

The stress of the pipe at plastic state can be determined by different equations, which can be easily included in the analysis. There are well defined models which can accurately predict the plastic deformation of the pipe using the limited parameter [25].

The most generalized stress-strain relationship from the elastic to the plastic limit is,

$$\sigma_t = \sigma_{ys} + K (\epsilon^p)^N \quad (20)$$



Where K and N are the material behaviour parameters

$$K = \frac{(\sigma_t - \sigma_y)^{1/N}}{(\varepsilon_p - \varepsilon_y)} ; \varepsilon^p = \left( \frac{\sigma_t - \sigma_y}{K} \right)^{1/N}$$

Equation (18) is the most widely used criterion for the plastic deformation behaviour of the material and it is called Ramberg-Osgood equation.

Using the Ramberg-Osgood equation for the plastic behaviour of the pipe, equation (19) becomes:

$$\frac{P_{max} D}{2} = (\sigma_{ys} + K (\varepsilon^p)^N) t_s + \sigma_c t_c \quad (21)$$

It is known that the strain in the composite laminate is  $\sigma_c = E_c \varepsilon_{cr}$ , so the above equation leads to:

$$P_{max} D = 2 \left( (\sigma_{ys} + K (\varepsilon^p)^N) t_s + E_c \varepsilon_{cr} t_c \right) \quad (22)$$

The equation (22) can be rearranged and the composite repair thickness is given as:

$$t_c = \frac{P_u D}{2 E_c \varepsilon_{cr}} - \frac{(\sigma_{ys} + K (\varepsilon^p)^N) t_s}{E_c \varepsilon_{cr}} \quad (23)$$

There are several models which can predict the theoretical plastic behaviour such as Ludwik, Hollomon, Swift and Ramberg-Osgood, etc. [25]. Consequently, the general equation of composite repair thickness with accounting for the plastic deformation of the pipe is:

$$t_c = \frac{P_u D}{2 E_c \varepsilon_{cr}} - \frac{\sigma_t t_s}{E_c \varepsilon_{cr}} \quad (24)$$

The above equation is used to determine the composite thickness for the design pressure ( $P_u > P$ ) using the allowable plastic deformation of the pipe ( $\sigma_t$ , pipe stress calculated at 50% of plastic strain) and composite material properties (strength of the composite,  $\sigma_c = E_c \varepsilon_{cr}$ ) for the safe repair design.

There is possible to determine the accurate strength capacity of the given composite material using the failure theories and this would help to refine the analytical model. The maximum sustained capacity of composite material strength ( $\sigma_c$ ) can be determined by the Tsai-Hill failure criterion, which is based on yield criterion and it is given by [26]:

$$\left( \frac{\sigma_{11}}{X_{11}} \right)^2 + \left( \frac{\sigma_{11} \sigma_{22}}{X_{11}^2} \right) + \left( \frac{\sigma_{22}}{X_{22}} \right)^2 + \left( \frac{\sigma_{12}}{X_{12}} \right)^2 \leq 1 \quad (25)$$

Where  $\sigma_{11}$ ,  $\sigma_{22}$  and  $\sigma_{12}$  are the longitudinal, transversal and shear stress respectively in a given lamina and  $X_{11}$ ,  $X_{22}$  and  $X_{12}$  are the universal longitudinal, transversal and shear stresses of the material respectively.

## 4. Results and Discussion

### 4. Composite repair thickness

Table 1 shows the calculated composite repair thickness based on different criteria and compares it with the new proposed plastic deformation model. Composite repair thickness based on the allowable strain criteria as proposed in the ISO/TS 24817 standard gives a very high conservative repair thickness, even though it is safer but not cost-effective. On the other hand, based on the composite strength, the same standard predicts a less conservative repair thickness values and most of the tests successfully sustain the design pressure except some tests [22]. However, in both criteria, the ASME PCC-2 standard predicts a lower conservative composite repair thickness, as this standard allows pipe yielding compared to the ISO/TS 24817 standard.

A high conservative composite repair thickness helps to avoid plastic deformation at the defect section of the pipe, however no guarantee regarding plastic deformation/ failure away from defect region. For example, Budhe et al. [16] found that the plastic deformation occurs quite away from the defect region and it may be due to the higher conservative repair thickness (Fig. 4). On the same line, Mazurkiewicz et al. [13] and Saeed et al. [27] reported plastic deformation and failure at the unrepaired section of the pipe (Fig. 5) and these are the consequences of higher composite repair thickness in the repaired pipe. Particularly, this higher conservative thickness is supported in terms of lack of data on the long-term performance of the composite sleeve of the repaired pipe in adverse condition and can accumulate the degradation. However, the new proposed model includes the plastic deformation (strain hardening) behaviour of the pipe in the analysis to evaluate the composite repair thickness.

It is found (see Table 1) that the proposed plastic deformation model is predicting a lower composite repair thickness than the ISO/TS 24817 and ASME PCC-2 standards. In the proposed analytical equation, the Holloman model is used to define the plastic deformation of the steel pipe and the plastic strain of the tested tube limited to 50% of the total strain for safe repair design. However, both the design codes ISO/TS 24817 and ASME PCC-2 restrict the pipe capacity up to or lower than yield stress, which is the main reason for the higher conservative repair thickness compared to the proposed model.

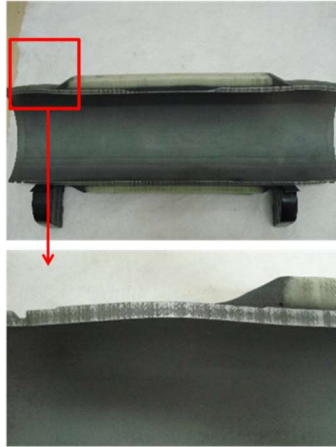


Fig.4. Plastic deformation of repaired pipe at away from defect region [16].

Table 1 Composite repair thickness based on different model and new proposed model.

Ref	Expt. Press (MPa)	Repair thickness (mm)	Failure pressure (ISO/TS 24817) (MPa)	Thickness based on allowable strain of composite (strain =0.004) (mm)		Thickness based on composite strength along circumferential direction (mm)		New proposed model based on plastic deformation Eq (25) (mm)
				ASME PCC2 Eq (16)	ISO TS 24817 Eq (18)	ASME PCC2Eq (17)	ISO TS 24817 Eq (19)	
Freire et al. [28]	27.90	25	23.25	50.90	57.32	25.45	28.66	22.34
	23.60	25	23.25	52.40	58.40	26.20	29.20	23.29
	23.50	25	23.25	53.12	58.92	26.56	29.46	23.75
	19.20	25	23.25	38.28	42.87	27.56	30.87	24.36
	22.80	25	23.25	36.63	41.69	26.38	30.02	22.85
	23.20	25	23.25	38.81	43.26	27.95	31.15	24.85
	23.50	25	23.25	34.81	39.83	22.93	26.24	19.73
Budhe et al. [16]	35.00	16.2	32.62	25.85	27.67	15.12	16.19	14.00
	35.90	16.2	32.62	25.85	27.67	15.12	16.19	14.00
	36.10	16.2	32.62	25.85	27.67	15.12	16.19	14.00
da Mattos et al. [22]	14.00	21.42	18.70	34.74	38.84	18.16	20.31	16.46
	14.20	21.42	18.70	34.74	38.84	18.16	20.31	16.46
	14.60	21.42	18.70	34.74	38.84	18.16	20.31	16.46

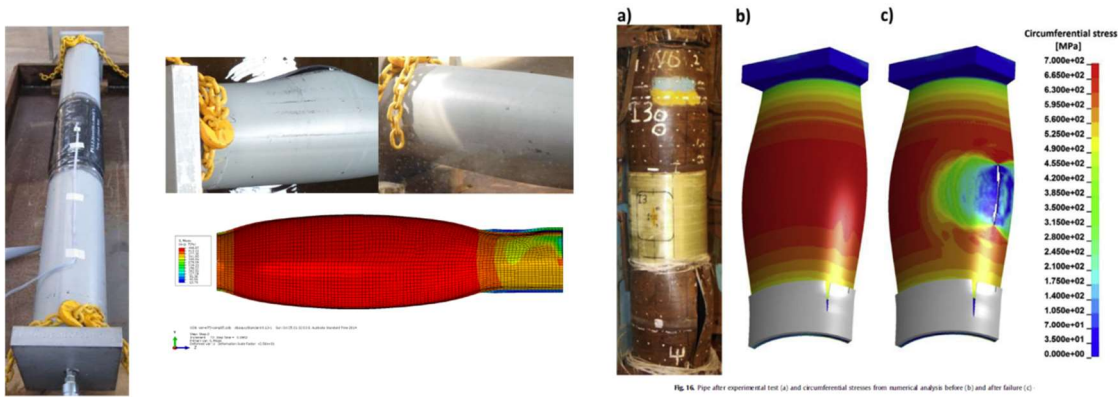


Fig.5. Failure and plastic deformation of repaired pipe away from the repaired/defect region, FE model also predict same failure (a) Saeed et al. [27] (b) Mazurkiewicz et al. [13].



Fig.6. Failure of repaired pipe at repaired/defect region [18].

Table 2 shows the calculated composite repair thickness based on the failure pressure of the repaired pipe using the new proposed model, design codes (ISO/TS 24817 and ASME PCC-2) and compare the results with the numerical models. It was found that the composite repair thickness obtained from the new model (strain hardening) is close to the numerical modelling results, where the composite failure takes place at the repaired section (Fig.6), however, the design codes (ISO/TS 24817 and ASME PCC-2) based on the elastic behaviour of the pipe shows very conservative repair thicknesses. In addition, other researchers [27, 13] used a higher conservative composite thickness even more than the ISO/TS 24817 standard for the repair of a corroded pipeline. This high composite repair thickness makes a stronger defect region than the pipe material which leads to fails at the unrepaired section of the pipe both experimental and numerical results (Fig.5). However, the proposed model predicts composite thickness which is lower than the used repair thickness to sustain the same failure pressure. This indicates that the optimal composite repair thickness is necessary and the proposed plastic deformation model predicts the pressure close to the experimental and numerical analysis [18, 20]. The proposed analytical modelling in this study provides a safe and accurate determination of composite thickness for

defective pipe which enable the saving of composite material for repair. In addition to that, the proposed model can be refined by accounting for the full capacity of the pipe material and filler material behaviour in the existing model.

Table 2. Composite repair thickness based on new model (plastic deformation) and compare with the numerical model results (FEM) and experimental results.

Reference	Expt. failure press. (MPa)	FEM failure pressure (MPa)	Failure location	Composite Repair thickness			
				Expt./ Num (mm)	Plastic deformation model (mm)	ISO/TS 24817 (mm)	ASME PCC-2 (mm)
Duell et al. [20]	43	44	at repair section	3.11	3.65	5.09	4.57
Lim et al. [18]	33	33	at repair section (Fig.6)	3.0	4.90	8.80	7.54
Saeed et al. [6]	37	stopped at 40	Outside repair section (Fig.5)	8.4	2.57	4.77	4.54
Mazurkiewicz et al. [13]	29.1	29.4	Outside repair section (Fig.5)	6.2	3.18	4.06	3.76

## 5. Conclusions

This paper presents a simple analytical model to estimate an accurate composite repair thickness with accounting for the pipe's plastic deformation behaviour and the results were compared with the ISO/TS 24817 and ASME PCC-2 design codes and numerical modelling. It was found that the composite repair thickness calculated based on the proposed methodology is less conservative (accurate) compared to both design codes ISO/TS 24817 and ASME PCC-2. The proposed analytical model predicts the composite repair thickness of repaired pipes which is in close agreement with the finite element numerical results. The composite repair thickness calculated based on the design code ISO/TS 24817 is highly conservative which results in some repaired pipeline to fail at an unrepaired section of the pipe. Hence, it would be useful to reduce and optimize the composite repair thickness which can sustain the design pressure and this would lead to a lower pipeline repair cost.

A larger number of hydrostatic tests of repaired pipes are necessary to assure the design code practices and validation of the analytical and numerical models. However, there is still the possibility to refine the analytical model by accounting for the failure of composite laminates using the Tsai-Hill or Tsai-Wu or Hashin failure theory, in addition to inclusion of the behaviour of the putty material in the analysis.

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## **Declarations:**

### **Funding**

No funding was received.

### **Competing interests**

The authors declare that they have no competing interests.

### **Availability of data and materials**

All relevant data are presented in the manuscript, if needed additional information may be made available upon request

### **Code Availability**

Program code is not used in this study.

### **Authors' contributions**

S. Budhe (First and corresponding author) was responsible for analytical data modelling and article writing part.

M.D. Banea carried out the analysis and made relevant changes in the manuscript.

S. de Barros carried out data analysis and comparison of experimental results with analytical and numerical model.

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