

Repair of filament wound composite pipes

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Abstract. Filament wound pipes are used in a wide variety of industries, due to the advantages composites have over metal pipes, such as a high strength to weight ratio, and resistance against frost, corrosion and heat. Composite pipes require minimal maintenance to ensure they are safe. Any damage occurring in composite pipes could lead to failure; therefore all damage should be assessed through NDT. If it is decided that the damage makes the pipe unsafe then a decision needs to be made whether to repair or replace the pipe. Repairing a composite pipe can be quicker, easier and cheaper than replacing it and can restore the strength of the pipe effectively. This investigation looks at the repair process and the parameters involved in determining the strength of the pipe following repair through the use of over 150 models in FEA software, Abaqus. Parameters considered include the pipe diameter and thickness, damage removal size and wrap width and thickness. It was found that if the pipe is thin-walled then it can be assumed that the pipe's thickness has no effect on the FOS following repair. Formulas were created to predict the FOS following repair for varying pipe diameters, damage sizes and wrap thickness. Formulas were also created to determine the wrap width required for varying wrap thicknesses and damage sizes.

1. Introduction

Filament wound pipes are readily used in a wide variety of industries, one example being the oil and gas industry. Composite pipes hold advantages over steel pipes due to being lighter, stronger and stiffer meaning less supports are required. They are also able to take greater loads and are resistant to frost, corrosion and heat, with minimal maintenance required. However if a filament wound pipe becomes damaged, there is the option to replace or repair. Damage mostly occurs at joints, fittings, bends, tees and reducers, with 49% being due to defective installation, 49% due to overloading of material due to shortcomings in design and 1% due to material defects [1]. Composites' strength also degrades with temperature elevations and moisture with the decrease in strength can be as high as 50-90% [2]. Damaged area should be removed with circular or oval shapes to avoid stress concentrations, but if this is not possible square or rectangular cut out can be used with rounded corners. A composite wrap can be used to repair pipes with diameters between 0.1 m and 1.42 m. It is 0.292 m long and needs to overlap the defect by 51mm on each side, if there is a large defect then multiple wraps can be used overlapped [3]. It is difficult to know the repaired pipe's new strength due to the number of parameter involved (pipe diameter and thickness, damage size, and the length and thickness of the wrap). Previous studies have considered the effect of the variation of individual parameters, but none have considered the effect of the parameters combined. This investigation considers these parameters

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and the effect they have on the factor of safety (FOS) of a damaged and repaired pipe through the use of FEA software. A total of over 150 models are analysed and the stresses and FOS are used to create formulas to predict the FOS following repair.

2. Literature review

Rousseau et al researched the influence of the winding pattern on the damage behaviour of filament wound glass/epoxy pipes under pressure with a $[\pm 55^\circ]$ layup. The winding pattern was varied through different degrees of interweaving to find that interweaving should be minimised [4]. Meanwhile, surface cracks were researched by Tarakçioğlu et al. by considering cracks of varying notch aspect ratios, notch to thickness ratios and winding angles under internal pressure. For the $\pm 55^\circ$ pipes they found that damage occurred at the notch tips of the pipe and then delamination occurred. The surface crack has the biggest effect on the burst strength for the $\pm 75^\circ$ winding angle [5]. Gemi et al. considered the progressive fatigue failure behaviour of glass/epoxy with a winding angle of $[\pm 75]_2$ under internal pressure. They found damage can be divided into three main steps, which starts with whitening and matrix cracking. The matrix cracking causes a leakage path to start forming from the inner side to the outer surface. Once the crack has reached the outside of the pipe failure occurs with catastrophic failure. They also concluded that if the applied load is high then the leakage and final failure coincides [6]. More recently Rafiee's work predicts the strength of GRP pipes with sand as a core material. The failure is modelled layer by layer, and once damaged the layer the mechanical properties are replaced by degraded properties [7]. Arikan considered inclined surface cracks, with varying crack angles, under static internal pressure in $[\pm 55^\circ]_3$ filament wound pipes. It was concluded that as the crack angle increased the burst pressure increases and the effect of the crack angle decreases [8]. Günaydın et al. considered the effects of composite repair patches and number of layers on the fatigue behaviour of surface-notched composite pipes. They found that out of the amount of layers tested the maximum was the most effective at preventing fatigue failure [9]. Repairing impact damaged composite pipes was investigated by Kara et al, who investigated the amount of layers required to effectively repair the pipe, finding that 6 layers are required [10].

3. FEA modelling of composite pipe

Abaqus FEA software was used to model the pipe when undamaged, with the damage removed and following repair. In order for longitudinal stress to be considered one end of the pipe is closed. The damage and wrap is modelled through the use of partitions with air, pipe and wrap properties being applied to the relevant regions. These properties are given in Table 1.

Table 1. Material properties of glass fibre and air.

	Glass fibre	Air	Units
Young's Modulus	-	0.01	MPa
Poisson's Ratio	0.3	0.03	-
long. modulus E1	120	-	GPa
trans. modulus E2	8	-	GPa
shear modulus G12	6	-	GPa
long. tension Xt	1800	-	MPa
long. comp. Xc	-1200	-	MPa
trans.tension Yt	80	-	MPa
trans. comp. Yc	-200	-	MPa
Shear, S	150	-	MPa

Figure 1 shows the design of the pipe modelled in Abaqus, with length of 1 m and pressure of 6 MPa applied. The pipe has a fibre orientation of $[54.75 -54.75]_4$, whilst the wrap has a fibre orientation of $[0\ 90\ 0\ 90]_s$. A mesh study was carried out to consider the amount of elements required to correctly

analyse the nominal and maximum stresses. Through considering the nominal stress, it was found that 6,600 elements were required to correctly analyse the nominal stress. This is equivalent to a node every 7 mm, but more elements were required for the maximum stress. Therefore the mesh was refined around the hole. Through the refinement mesh study it was found that 15 elements per line were required for refinement. This brings the total amount of elements to 8, 860 elements, which is shown in Figure 2. This mesh is structured with the elements being quad-dominated.

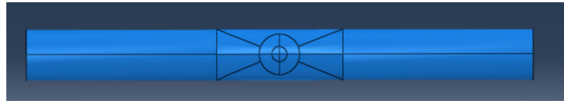


Figure 1. Design of pipe model.

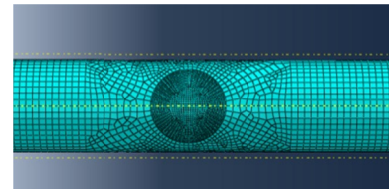


Figure 2. Mesh applied to models.

4. Effect of pipe diameter on FOS

Pipe diameter varies dramatically with applications therefore it is important to understand how pipe diameter affects effective pipe repair. In this investigation the FOS of the pipes prior and following damage and following repair are considered to obtain an understanding of the effect of removing damage and repairing a pipe for different size pipes: 0.1 m, 0.3 m and 0.5 m. This was done through the use of 9 initial FEA models. First to be considered was the effect of pipe diameter on the damage removal FOS, with the results shown in Figure 3, where FOS reduction factor is as defined in equation (1). These results were then used to create equation (2).

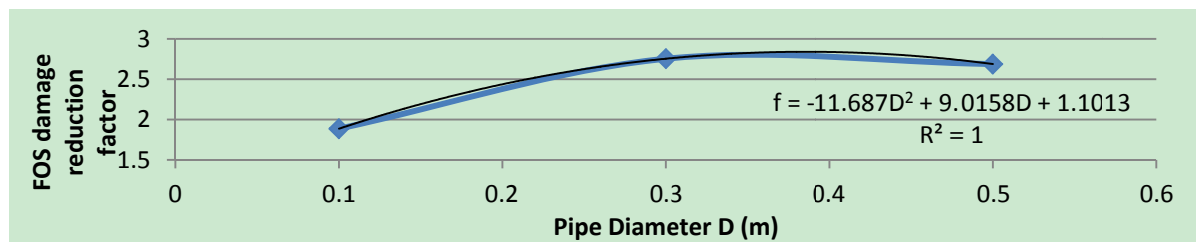


Figure 3. FOS damage reduction factor for varying pipe diameters.

$$FOS \text{ reduction (or gain) factor } (f) = \frac{FOS_{prior}}{FOS_{after}} \quad (1)$$

$$FOS_{after \text{ damage removed}} = \frac{FOS_{prior \text{ damage}}}{-11.687D^2 + 9.0158D + 1.1013} \quad (2)$$

Next the repair of damage was considered, by considering the relationship between FOS before repair and following. From the results equation (3) was produced to predict the FOS following repair if the FOS after damage removal is known. Often the middle stage of repair is not of interest; therefore results already obtained were used to consider the relationship before damage and after repair for varying pipe diameters to create equation (4).

$$FOS_{after \text{ repair}} = \frac{FOS_{after \text{ damage removed}}}{3.1873D^2 - 2.1499D + 0.708} \quad (3)$$

$$FOS_{after \text{ repair}} = \frac{FOS_{prior \text{ damage}}}{2.7236D^2 - 1.2208D + 1.0848} \quad (4)$$

These three equations are accurate for pipes with a diameter of up to 0.5 m. In order to determine the accuracy of these formulas an additional two pipe diameters (0.05 m and 0.2 m) were analyzed. It was found that the maximum percentage difference between FEA results and that predicted by the formulas was less than 5%, giving the formulas an accuracy of 95%.

5. Effect of pipe thickness on FOS

In this investigation thin-walled pipes are considered, this means that the thickness should be less than 10% of the radius of the pipe. As with the previous investigation the three stages (undamaged, damaged and repaired) are considered for the three pipes, giving a total of 9 models to be analysed. Six of the models were analysed to obtain an understanding of the effect of the thickness of the pipe on the FOS when removing damage. These results were used to create equation (5) to predict the FOS following damage removal for varying pipe thicknesses. To consider the repair of damage, the FOS following damage removal results were used and an additional three model (of varying thicknesses with wraps) should be analysed. These results can then be used to create equation (6) to predict the FOS following the wrap being applied.

$$FOS_{after\ damage\ removed} = \frac{FOS_{prior\ damage}}{0.0174T^2 - 0.178T + 2.1234} \quad (5)$$

$$FOS_{after\ repair} = \frac{FOS_{after\ damage\ removed}}{-0.0066T^2 + 0.0669T + 0.449} \quad (6)$$

When considering the effect of the pipe diameter it was mentioned that often the FOS after damage but before repair is often not of interest. Therefore Figure 4 shows the overall reduction factor from, comparing before damage and after repair and this was used to create equation (7).

$$FOS_{after\ repair} = \frac{FOS_{prior\ damage}}{-0.0012T^2 + 0.01T + 1.0109} \quad (7)$$

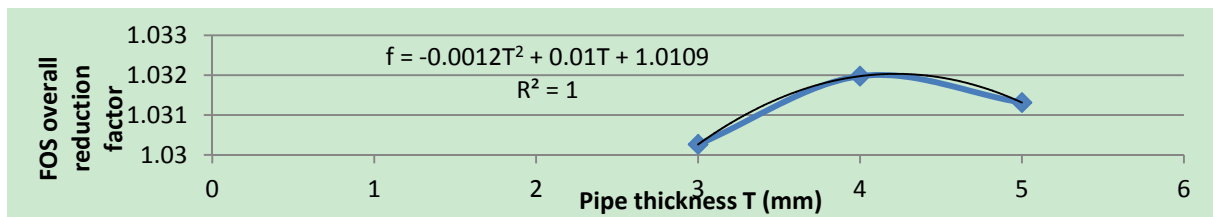


Figure 4. Overall FOS reduction factor with varying pipe thicknesses.

From Figure 4 it can be seen that the FOS overall reduction was constant despite the thickness of the pipe at approximately 1.03. Therefore it should be considered whether the FOS overall reduction factor is constant if the pipe is thin walled. This was done through additional pipe thicknesses of 3 mm and 15 mm to model six additional FEA models. From the results it was found that the overall FOS reduction factor was 1.03 and 0.9963 for the 3 mm and 15 mm pipes respectively. This is a difference of 0.04, for a thickness difference of 12 mm. Therefore it can be stated that the thickness of the pipes has no impact on the final FOS for thin walled pipes.

To gain an idea of how accurately the equations created can predict FOS, two additional thicknesses were considered (2 mm and 3.5 mm). These were modelled in Abaqus and the FEA results were compared with results obtained from the equations. The repaired FOS can be accurately obtained from the formulas created. In fact it was found that this formula had an accuracy of 99%. However the formulas did not predict the damaged FOS very well, with only an accuracy of 66%. These formulas are valid for pipes which are thin walled.

6. Effect of damage removal size on FOS

Damage comes in all different sizes and as little as suitable area surrounding the damage should be removed. Therefore it is required to investigate into the effect of different damage sizes. In this study, three initial studies of varying damage sizes are considered: 30 mm, 50 mm and 70 mm, through 7 models analysed in Abaqus. To consider the removal of damage, four of the models were analysed and the minimum FOS was taken from each model. These models were of the pipe prior to damage and after damage removal. These FOS were then used to obtain equation (8). The effect of repairing damage was considered to obtain equation (9).

$$FOS_{after\ damage\ removed} = \frac{FOS_{prior\ damage}}{-222.32d^2 + 27.228d + 0.839} \quad (8)$$

$$FOS_{after\ repair} = \frac{FOS_{after\ damage\ removed}}{117.05d^2 - 14.232d + 1.1695} \quad (9)$$

From all the results collected the overall gain or loss of strength can be considered, by looking at before damage and after repair. From these results were used to obtain Figure 5 and equation (10). It was noticed that the overall FOS gain factor varies very little for different damage diameters.

$$FOS_{after\ repair} = \frac{FOS_{prior\ damage}}{2.6216d^2 - 0.2097d + 1.2382} \quad (10)$$

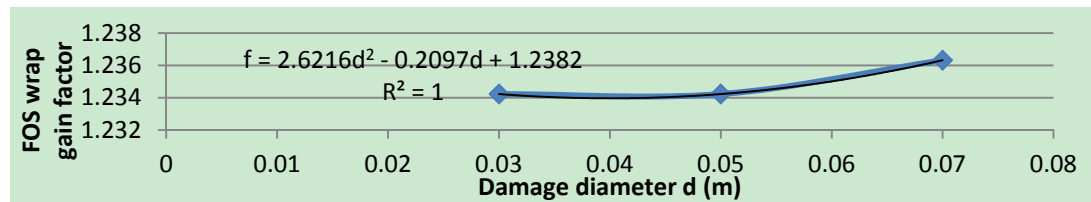


Figure 5. FOS overall gain factor.

To determine the accuracy of the formulas created in this section, an additional scenario was considered with damage of 40mm under the same conditions as previously. Two additional models are produced: before damage, following damage and following repair. The results from FEA are then compared with the FOS predicted from the formulas. It was found that there is a good comparison between FEA and the formulas created. The formulas can accurately predict the FOS once repaired, with a reliability of 99.98%. However there was a percentage difference of 38% between formulas and FEA for predicting before repair. These formulas are valid for damage sizes between 0.03m and 0.07 m.

7. Effect of damage removal shape on FOS

It is not always possible to remove damage with a circular hole, due to the geometry and the size of the damage and component. In these cases, a square cut out with rounded corners should be used instead. From a previous study the worst case scenario of a square cut out was considered and it was found that the best angle to remove damage is at 45° [11]. Therefore, an investigation was carried out to determine the difference in using a square cut out at 45° with a circular cut out. To make the shapes comparable the area between the cut out shapes were kept constant, as shown in Table 2, and the FOS following damage removal. Figure 6 and Figure 7 shows the results obtained. As expected as the damaged area increases, the FOS decreases. By using a square cut out the FOS is dramatically less than using a circular cut out. For each scenario it was found that the FOS following damage removal is 60% less if a square cut out rather than a circular cut out. It can be seen that the FOS following repair is approximately the same whether a circle or square is used to remove damage, with the square cut out FOS being only 0.5% less than the circular cut out. Therefore it can be stated that as long as a suitable wrap is used then it does not matter what shape is used to remove the damage.

8. Effect of wrap thickness

An investigation was carried out into the effect of varying the wrap thickness between 0.3 mm and 3.5 mm. A total of 9 models were considered and analysed using FEA software and from the results the minimum FOS was noted for each wrap thickness and used to create

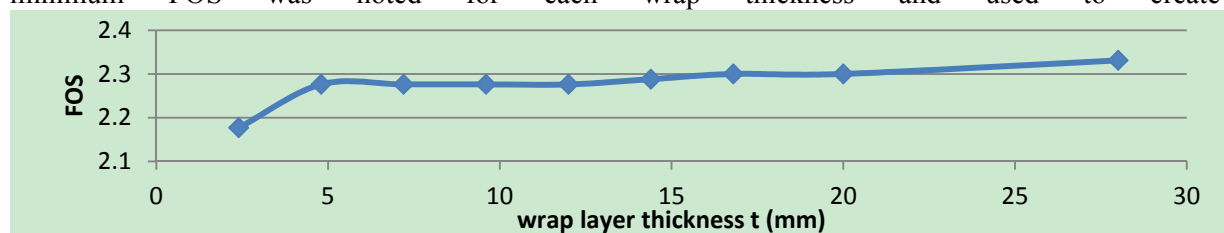


Figure 8. As expected as the thickness of the wrap increases the FOS also increases. There is a large

jump in the FOS between 2.4 and 4.8 mm, therefore a minimum thickness of 4.8 mm is suggested in this scenario.

Table 2. Damage Removal Shape Investigation Scenarios.

Scenario	Area (m ²)	Circular cut out diameter (m)	Square cut out side length (m)
1	7.069E-4	0.03	0.0266
2	1.9635E-3	0.05	0.0433
3	3.8485E-3	0.07	0.062

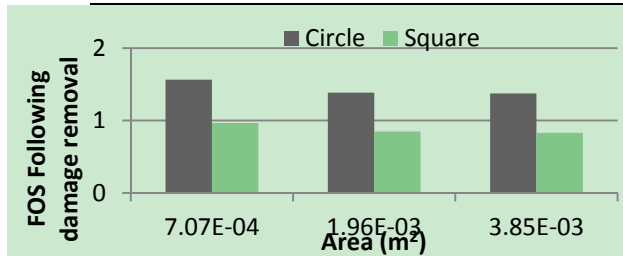


Figure 6. FOS following damage removal with varying cut out shapes.

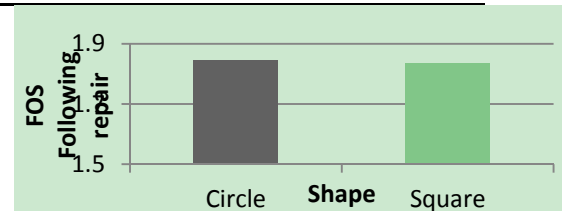


Figure 7. FOS following repair for varying cut out shapes.

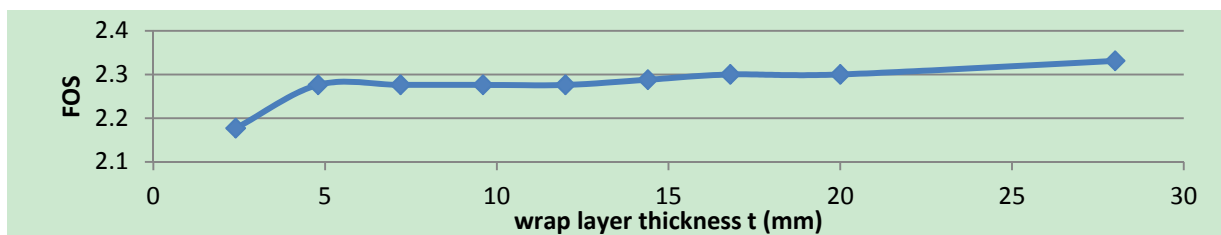


Figure 8. Wrap thickness investigation FOS.

9. Investigation into wrap width

Wrap manufacturers recommend at least 51mm of wrap either side of the damage, their standard wrap width is 292 mm. This section looks at whether this much wrap is actually needed either side of the damage. If the wrap is too short then it's possible that the wrap will not be able to deal with the stress concentrations caused by the hole and risk failure. But a wrap width of too much will waste material, money and time. Therefore three wrap thicknesses (13 mm, 8 mm, and 4 mm) and three damage sizes (30 mm, 50 mm and 70 mm) were considered in an extensive trial and error method of 70 models to determine the optimum wrap width for each scenario. The results can be seen in Figure 9, which is valid for wrap thicknesses between 4 mm and 13 mm and damage sizes between 0.03 m and 0.07 m.

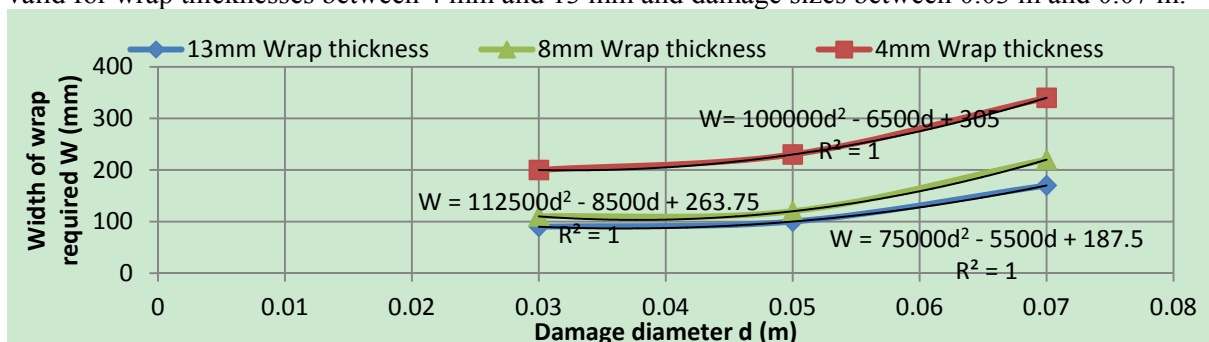


Figure 9. Wrap width investigation- Wrap width against damage size for varying wrap thicknesses.

10. Conclusion

In this investigation the parameters involved in repairing filament wound pipes are studied. The first parameter to be considered was the pipe diameter to create formulas to predict FOS following damage

and FOS after repair, with a reliability of 95%. It was found that if the pipe is thin-walled then it can be assumed the pipe thickness has no impact on the FOS following repair.

The damage size was considered and formulas were created to estimate the FOS of the pipe when damaged and repaired. When checked with an additional scenario it was found that the FOS following repair could be predicted with an accuracy of 99.98% with the formulas created. However it was also found that the FOS after damage removal and before repair could only be predicted with an accuracy of 72%. However this FOS is not commonly of interest as the pipe will be repaired straight after damage removal.

The wrap was then investigated by looking at thickness and width. As expected it was found that as the wrap thickness increased the FOS following repair increased. An extensive trial and error method was used to investigate the wrap width for nine scenarios with varying damage sizes and wrap thicknesses. From this equations were created to predict the FOS before and after repair with an accuracy of 98%. It was also found that if T/D is constant then the wrap width required is the same length.

Through more than 150 models this investigation has provided useful equations to predict the FOS following damage and repair, which will save time and correct repair methods in industry. However experimental testing should be carried out to confirm findings.

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