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Study of Tube And Tank Specimens Repaired Using a Carbon Fibre Reinforced Epoxy

Abstract

Merchant and passenger ships operate in harsh environments where they constantly suffer from corrosion and crack problems. The traditional cutting and welding of the steel parts most often requires redirection of a vessel to a shipyard what results in substantial vessel out-of-service time. In such situations, a ship operator seeks an efficient and fast repair solution to minimise ship delays. Following advancements in research and application of composite materials, an opportunity to implement composite patches made of carbon fibres and epoxy resin has emerged in the shipping industry as one of the cost and time efficient repair solutions. Although, the resin hardens and bonds the fibres strongly to the damaged surface, classification societies still consider this repair as a temporary solution and accept it conditionally, meaning with the frequent obligatory inspections. This is because there hasn't been enough practical evidence yet to recognise the composite patching as the permanent repair solution. In order to further investigate the efficiency of the composite patching, this paper presents the finite element (FE) strength investigation of 17 patches applied to tube and tank specimens under water pressure. The future work will consider a validation of the obtained FE results by means of pressure testing during the course of the qualification process.

Keywords: Carbon Fibre, Epoxy Resin, Adhesive Joining, Repair of Steel, FEM

1. Introduction

Merchant and passenger vessels, such as tankers or bulk carriers, operate in harsh environments, enduring corrosion and cyclic force and thermal loads that lead to various forms of vessel damage and defects as presented in Figure 1, endangering people and cargo, as well as posing a risk to the environment in some cases.

Figure 1: Frequent problems of corrosion and cracks on various positions on different vessels

In such situations, each ship-owner or operator company seeks an effective and fast repair solution in order to: reduce potential risks, assure alignment with the international maritime regulations and minimize the time delays to its ships, which leads to a loss of revenue if a ship is taken out of service for a repair by traditional approach of steel cutting and welding. Such approach requires redirection of a vessel to a shipyard resulting in substantial vessel downtime, which results in mentioned loss of revenue and also large expenses for a repair. The traditional approach requires a replacement of a part of ship structure, even when a problem is present only in a small section. In addition this method requires the removal of parts, equipment or ship interior details, leading to greater expense and additional downtime to execute the repair. Most importantly, the welding cannot be applied in all areas of a ship since some locations are adjacent to fuel tanks and pose a potential fire risk, causing a cutting and welding procedure to be dismissed if fuel tanks are not emptied and properly cleaned before the repair. In such cases, a bonded patch repair based on fibre reinforced polymer (FRP) is a potential cost and time efficient repair solution [1]. This solution utilises fibres mixed with polymer resin. By curing, the resin hardens and bonds the fibres to the damaged surface permanently and the resulting composite material patch reinstates the damaged material's strength and provides water tightness; see Figures 2 and 3 for more information.

Figure 2: Steel tube before (left) and after the repair (right)

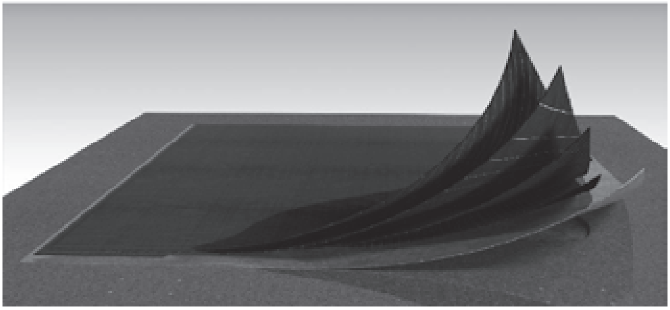

Figure 3: Schematic composite patch layup

This kind of composite repairs entered the service in aviation industry more than 30 years ago and were functionally used for crack repairs [2] and structural reinforcements [3]. The recent overview [4], among mentioned functionalities, also showed that the composite repairs are very cost effective. Some years later, the composite repairs were also used to repair cracks and corrosion on ships and marine offshore installations [5-7]. The composite patches used on board ships proved to be very durable and were reported to be functional even after more than 10 years in service [8]. The EU funded project "CO-PATCH" made progress with designing patches for typical repairs on board ships and also showed that it is possible to monitor repaired cracks using strain gauge technology [9]. In parallel, composite repairs were also used in civil engineering for buildings and bridges [10]. Regardless of the industry branch, it seems that the most of applications and research efforts were focused on corroded and leaking pipes [11, 12]. Consequently, many commercial products in a form of repair kits for composite repair of pipes emerged over the years and some of them were discussed in [13]. However, the unanimous opinion of the classification societies that have the authority over approval of the repairs in shipbuilding, is that there is still not enough practical evidence to support the claims that the composite repairs should be recognised as the permanent or in some cases even as temporary repairs in shipping industry.

This paper investigates composite patches applied to the leaking tank and tube specimens. The study conducts a finite element (FE) analysis of the patched specimens in order to investigate if the applied patches can withstand peak pressures necessary for the typical tubes and tanks on board ships in service.

2. Analysis

Two specimens were modelled and analysed. The first one is a steel tank being repaired using 16 composite patches (8 inside and 8 outside of the tank) subjected to the internal pressure of 3 bar; see Figure 4 for a schematic representation and accurate drawings in Figure 5.

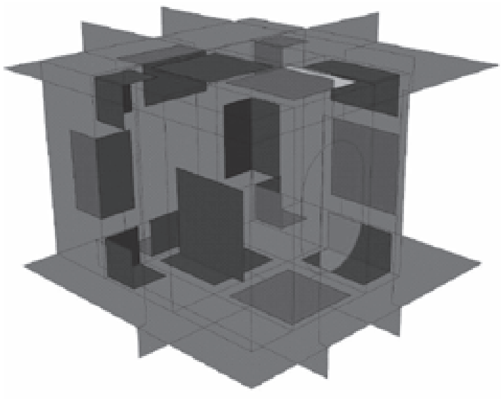

Figure 4: Schematic representation of the tank specimen (I – patch on the inner side (magenta); O – patch on the outer side (green))

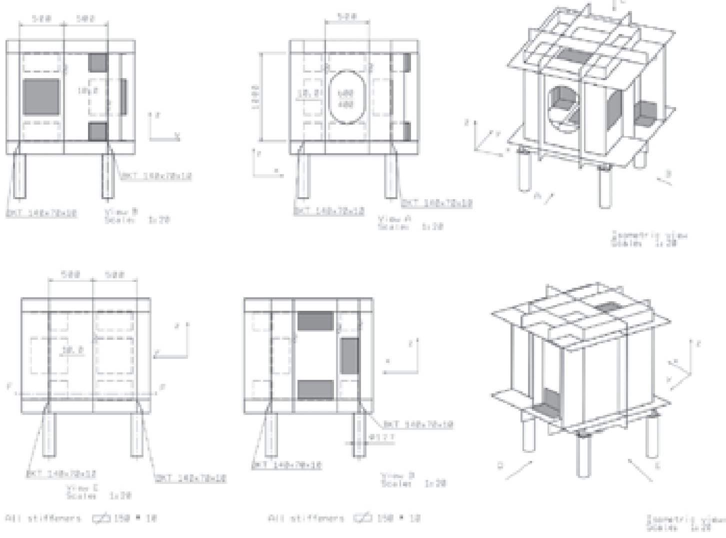

Figure 5: Drawings of the tank specimen

Each of the 16 patches is used to repair a small circular hole, which has an area of 1 cm^2 and is located exactly in the middle of the patch. Therefore, depending of the patch, some holes are located at the flat plating and some are located at the intersection of two or three flat plates. The second specimen is a steel pipe with one composite patch analysed under pressure of 15 bar and is presented in drawings in Figure 6. There is the same size small-hole in the middle of the patch within the pipe specimen as well. Both analyses were conducted in Ansys 19.2 APDL software.

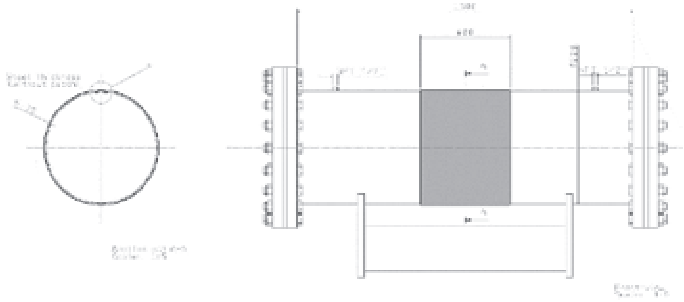

Figure 6: Drawings of the pipe specimen

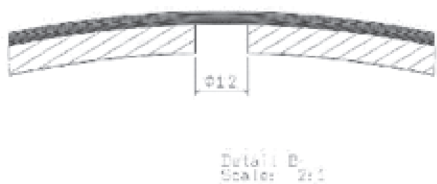

Figure 7: Drawing of the Detail B from the drawing of the pipe specimen

2.1. Material models and properties

Composite patch layup consists of 3 layers of Chopped strand glass 300 g/m^2 and 4 layers of Bi-Axial 0/90 carbon 300 g/m^2. The resin used is West System 105 with the hardener type 205. The material properties are used as specified by the manufacturer. In FE model, the steel and resin (epoxy) are modelled as isotropic elastic materials, whereas the glass-epoxy and carbon-epoxy are modelled as orthotropic elastic materials. All material properties are given in Table 1.

Table 1: Material properties

	Steel	Adhesive	Glass	Carbon
Model	Linear Elastic Isotropic	Linear Elastic Isotropic	Linear Elastic Orthotropic	Linear Elastic Orthotropic
Density (kg/m^3)	7850	1300	1680	1500
Elastic modulus (MPa)	E=206000	E=2810	E11=26187* E22=5532 E33=5532	E11=149186* E22=5959 E33=5959
Shear modulus (MPa)	-	-	G12=2486 G13=2486 G23=1740	G12=3197 G13=3197 G23=2238
Poisson (-)	ν=0.3	ν=0.35 (assumed to be)	ν12=0.306 ν13=0.306 ν23=0.306	ν12=0.231 ν13=0.231 ν23=0.166
Tensile breaking stress (MPa)	-	σ=55	σ1T=707 σ2T=23 σ3T=23	σ1T=1044 σ2T=24 σ3T=24
Compressive breaking stress (MPa)	-	-	σ1C=471 σ2C=86 σ3C=86	σ1C=671 σ2C=125 σ3C=125
Breaking shear stress (MPa)	-	-	τ12=45 τ13=31 τ23=62	τ12=58 τ13=40 τ23=58
Deformation	-	3.4 %	-	-

**1 - fibre direction, 2 - perpendicular to fibre*

2.2. Element type and mesh

For both models, the structure and composite patches are discretised by 8-node structural shell elements SHELL281 with element size of 50 mm. This type of element is suitable for layer-type of modelling a composite material. The steel is modelled as isotropic elastic material with Young's modulus of 210.000 MPa and Poisson's ratio of 0,3. The default element edge size is 45 mm in this study.

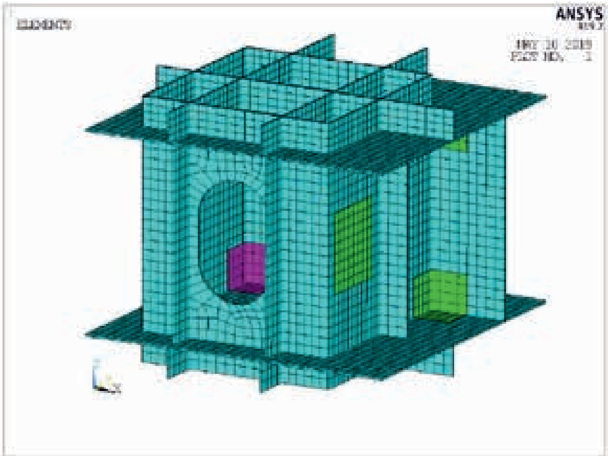

Figure 8: FE model of tank with patches

Composite patches are modelled as layered shell elements with layup as shown in Table 2, which represents a typical layup used for the repairs. The model is made in a way that the composite patch elements are sharing the same nodes as their adjacent steel elements. For composite patch elements, one layer of Bi-Axial 0/90 carbon fibre 300 g/m^2 is modelled as two unidirectional carbon fibre 150 g/m^2.

Table 2: Composite patch layup

Layer	Thickness (mm)	Orientation (deg)	Fibre
Layer 1	0.357	-	Chopped strand glass fabric 300 g/m^2 with Epoxy resin
Layer 2	0.357	-	
Layer 3	0.357	-	
Layer 4	0.2	0	Unidirectional Carbon fibre 150 g/m^2 with Epoxy resin
Layer 5	0.2	90	
Layer 6	0.2	0	
Layer 7	0.2	90	
Layer 8	0.2	0	
Layer 9	0.2	90	
Layer 10	0.2	0	
Layer 11	0.2	90	

Steel structure of tank has a thickness of 10 mm, and adhesive (Epoxy resin) has thickness of 0.2 mm. All layers in the model can be seen on the left side of Figure 9.

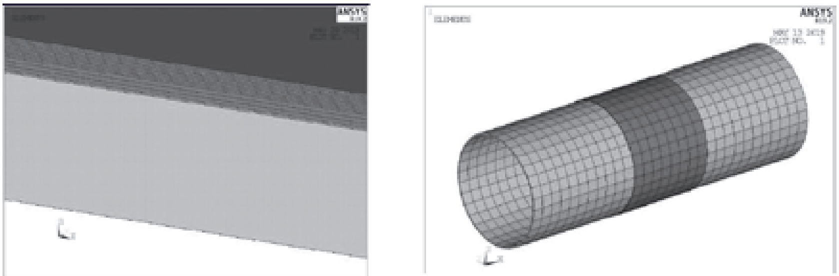

Figure 9: Left: Detail of layered elements in part of tank structure with inner patch (blue represents steel, orange represents adhesive and magenta composite layers); Right: FE model of the pipe with the patch

Regarding the model of pipe, composite patch has the same layup as in the tank model, but the steel structure has a thickness of 6.35 mm which is a standard thickness for pipe DN500 that is certified for the pressure of 15 bar. FE model of the pipe structure with composite patch is shown on the right side of in Figure 9.

2.3. Analysis of the patched tank

The tank specimen has overall dimensions of 1.6x1.6x1.3 m. The geometry can be seen in Figure 5 and 8, where composite patches are denoted in Figure 8 by magenta colour for inner patches and by green colour for patches on the outer side of the tank. The pressure of 3 bar was applied in the inner side of the tank dimensions 1x1x1 m; see Figure 10.

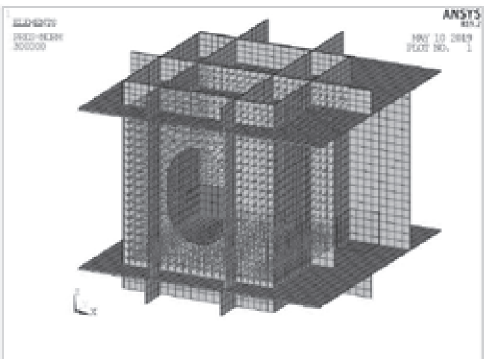

Figure 10: Applied pressure load of 3 bar to the tank interior

In order to simulate hole in the steel plate, a force of 30 N was applied in one node in in the middle of the external (green) patches; see Figure 11. The force of 30 N corresponds to the pressure of 3 bar acting on the hole-area of 1 cm2.

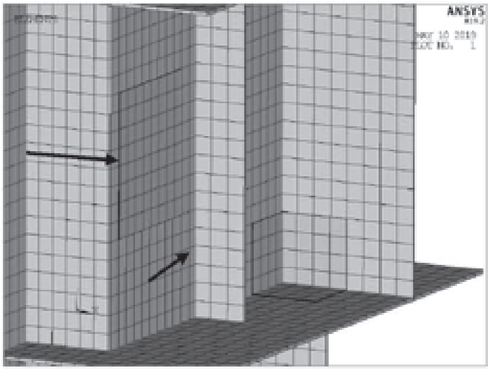

Figure 11: Left: Applied force load of 30 N to the middle node of the external patches

The model boundary conditions for both load cases are shown in Figure 12.

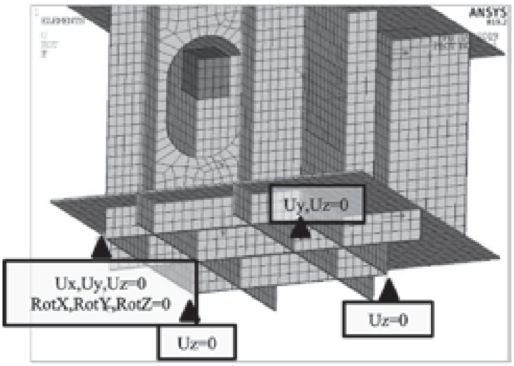

Figure 12: Left: Applied boundary conditions

2.4. Analysis of the patched pipe

Standard steel DN500 pipe with length of 1.5 m and thickness of 6.35 mm was analysed. Composite patch with length of 400 mm was placed in the middle of the outer side of the pipe and around the entire pipe diameter. The geometry can be seen in Figure 13, where the composite patch is depicted by magenta colour.

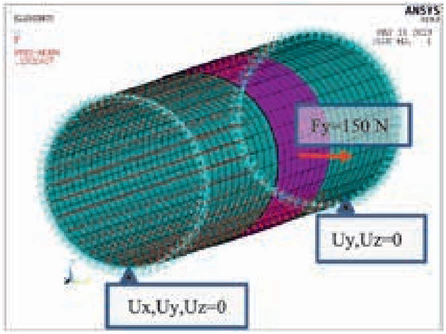

Figure 13: FE model of the patched pipe specimen showing pressure and boundary conditions

Patched pipe was analysed under pressure of 15 bar. The pressure was applied in the inner side of the pipe (see Figure 13). In order to simulate crack / hole in the steel part, a force of 150 N was applied in one node in in the middle of the patch. The force corresponds to the pressure of 15 bar acting on the hole of 1 cm^2. Boundary conditions are also shown in Figure 13. On one side of the pipe, displacements in all directions are supressed and on the opposite side, displacements only in y and z direction are suppressed.

3. Results

3.1. Tank specimen

The results of the analysis show that the total displacement is 4.7 mm in the middle of the red coloured area shown on the side of the specimen in Figure 14.

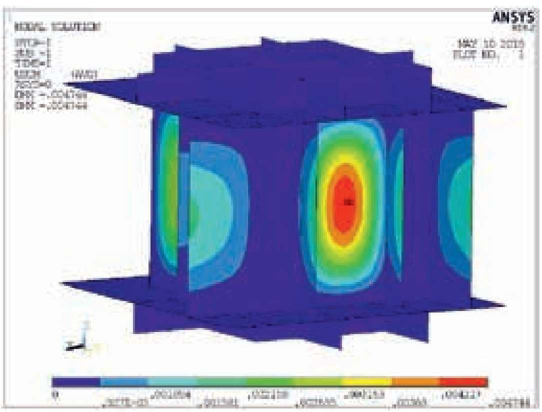

Figure 14: Displacement vector sum in m

Maximum von Mises stress in steel structure is 352 MPa (see Figure 15) that occurs in the area of weld between vertical plates and stiffeners, i.e. in the junction of plates and stiffeners. This is an unrealistic concentration of stress in nodes which can be neglected because the weld area was omitted from the model.

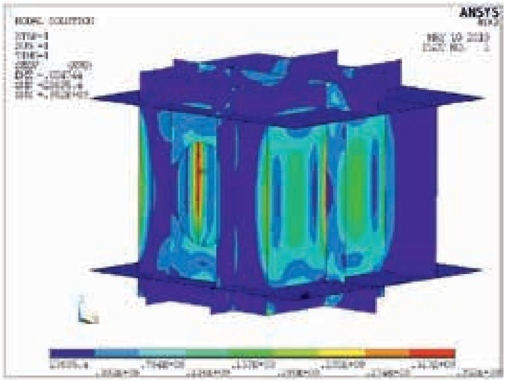

Figure 15: Von Mises stress plot

The remaining structure has a Von Mises stresses well below the maximum permissible value of 282 MPa. The maximum permissible von Mises stress for steel is 282 MPa and it was calculated according to DNV-GL Rules for classification, Pt3 Ch7 Finite element analysis. There, the maximum permissible stress is calculated according to the fine mesh yield utilisation factor .

$$\lambda_f = \frac{\sigma_{vm}}{R_Y} \leq \lambda_{fperm}, \tag{1}$$

Where σ_{vm} is von Mises stress, R_Y is nominal yield stress ($R_Y = \frac{235}{k}$, k is a material factor equal to 1 in this case), and is permissible fine mesh utilisation factor which is taken as 1.2 as a most conservative for elements adjacent to weld.

$$\sigma_{vm} \leq \lambda_{fperm} * R_Y = 1.2 * 235 = 282\,MPa, \tag{2}$$

Regarding the adhesive layer between steel structure and the composite patches, the results show that stresses and strains are far from the breaking limits given by the manufacturer for the West System Epoxy Resin 105 used here as the adhesive material. For the simplicity, only the strains were given here in Figure 16.

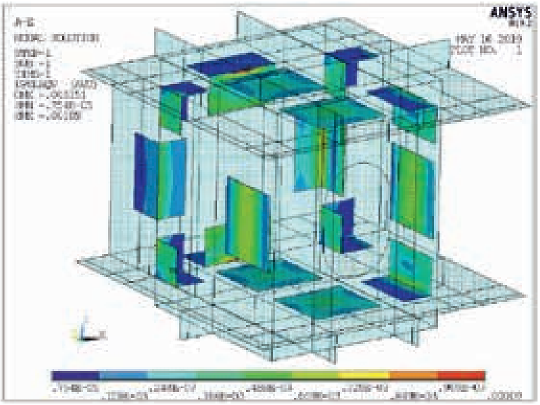

Figure 16: Von Mises strain plot

Maximum von Mises elastic strain in adhesive is only about 0.1%, which is far from the breaking limit of 3.5%, indicating that the adhesive is safe from breaking.

The failure in composite patches consistent of layers of glass/epoxy and carbon/epoxy fibres is observed through Tsai-Wu failure criteria [14] i.e. the material will fail if maximum Tsai-Wu failure criteria index exceeds 1. Also, the stress levels are being considered for each patch and each layer (ply). The Tsai-Wu index and maximum stresses are shown in Table 3. These values represent maximum recorded values in each layer among all 16 patches. The maximum stresses always occur in the outermost layer, but the values are far from the breaking point.

Table 3: Maximum stresses in layers taken from all 16 composite patches

Layer no.	TWSI	Normal stress			Shear stress		
		S_X (MPa)	S_Y (MPa)	S_Z (MPa)	S_{XY} (MPa)	S_{XZ} (MPa)	S_{YZ} (MPa)
Layer 1	0.19	20.31	10.86	30.80	1.38	2.40	1.95
Layer 2	0.20	21.74	11.57	32.98	1.46	2.54	2.07
Layer 3	0.22	23.17	12.29	35.15	1.55	2.68	2.19
Layer 4	0.24	134.21	67.72	203.63	2.05	3.54	2.91
Layer 5	0.19	157.32	194.66	213.44	2.11	3.64	3.00
Layer 6	0.26	143.41	72.01	217.25	2.17	3.74	3.09
Layer 7	0.21	167.10	206.89	227.15	2.23	3.84	3.17
Layer 8	0.28	152.61	76.29	230.87	2.29	3.94	3.26
Layer 9	0.22	176.87	219.12	240.87	2.35	4.03	3.35
Layer 10	0.29	161.80	80.58	244.50	2.41	4.13	3.44
Layer 11	0.23	186.65	231.35	254.58	2.47	4.23	3.53

3.2. Pipe specimen

The response of the steel material of the pipe specimen shows that the total displacement is 0.13 mm, whereas the maximum von Mises stress is 74.3 MPa (see Figure 17).

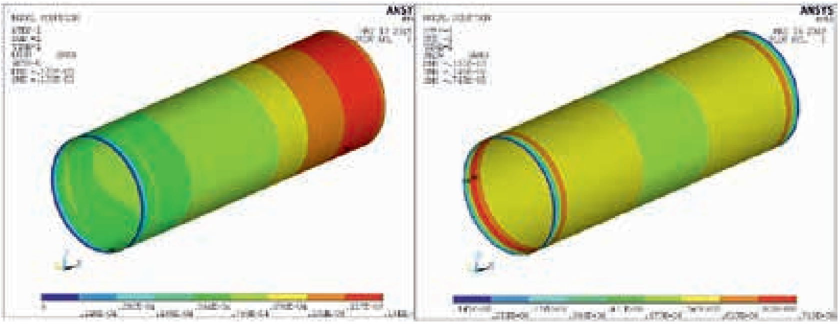

Figure 17: Left: Resulting displacement vector; right: Von Mises stress plot

The stresses and strains are far from the breaking limits in the adhesive layer; see Figure 18 for the strain plot.

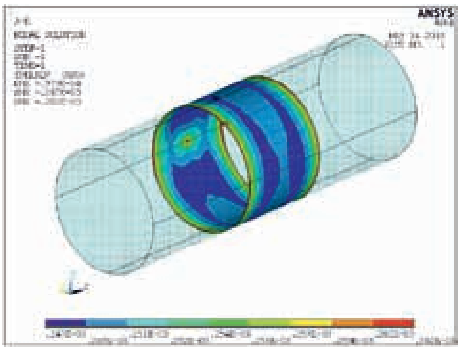

Figure 18: Von Mises strain plot

The stress levels and the Tsai-Wu indexes are given in Table 4, showing that all values are far below the limits.

Table 4: Maximum stresses and Tsai-Wu index for the composite patch of the pipe specimen

Layer no.	TWSI	Normal stress			Shear stress		
		S_X (MPa)	S_Y (MPa)	S_Z (MPa)	S_{XY} (MPa)	S_{XZ} (MPa)	S_{YZ} (MPa)
Layer 1	0.0462	1.633	1.370	1.396	0.005	0.005	0.684
Layer 2	0.0464	1.650	1.369	1.402	0.008	0.008	0.683
Layer 3	0.0466	1.668	1.368	1.409	0.010	0.010	0.683
Layer 4	0.0568	11.464	1.476	1.520	0.014	0.014	0.737
Layer 5	-0.0183	0.128	39.100	40.079	0.014	0.014	19.513
Layer 6	0.0570	11.566	1.475	1.527	0.014	0.014	0.736
Layer 7	-0.0181	0.133	39.031	40.230	0.014	0.014	19.479
Layer 8	0.0571	11.669	1.473	1.534	0.013	0.013	0.735
Layer 9	-0.0179	0.138	38.963	40.381	0.009	0.011	19.445
Layer 10	0.0573	11.771	1.471	1.542	0.009	0.012	0.735
Layer 11	-0.0177	0.143	38.894	40.531	0.003	0.012	19.411

4. Conclusions

This paper considers a carbon-fibre reinforced epoxy composite patches as the repair method for tanks and pipes on board ships in service. The repair method lacks testing and analysis before it gets recognised as an acceptable method. To investigate the ability of the composite patches to withstand typical pressures imposed to tanks and tubes on board ships, this paper conducted the finite element strength analysis of the patched tank and tube specimens. Based on the FE analysis, this study strongly suggests that the stress levels in the composite patches are very small even for the significant pressures in tanks (3 bar) and pipes (15 bar) and that these patches should be further investigated as the repair method.

The future work should consider the same specimens analysed within this study, but physically manufactured and tested by means of standard pressure testing in order to validate the results and conclusions from this study. Such testing would not only investigate the efficiency of the patches, but it would also investigate an accuracy of the FE method when assessing composite patches, noting that the FE method, so far, proved to be accurate and suitable for investigation of patches [11, 12].

Acknowledgements

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