Analysis of the Effects of Crack Location on the Fracture Behavior of Mechanically Stressed Pipelines Repaired with Composite Patches

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Abstract: This study employs the finite element method to analyze the fracture stress distribution in pipelines repaired with composite patches. Key factors examined include the crack location and fiber orientation within the composite patch. The impact of these factors on damage propagation and repair effectiveness is assessed. Additionally, the stress distribution in the adhesive layer is analyzed to estimate the durability of the repair technique. The study further evaluates the effectiveness of the repair by varying the debonding zones within the adhesive layer.

Keywords: Finite Element Method, Mechanically Stressed Pipelines, ABAQUS.

1. INTRODUCTION

In the field of fluid transport, particularly for oil and gas, current policies aim to reduce the weight of structures while maintaining their rigidity and strength. Laminated composites are increasingly used to meet these demands due to their high strength-to-weight ratio and excellent mechanical properties . The widespread adoption of composite structures in the transport industry hinges on the reliability of the associated assembly methods. In this context, adhesive bonding offers numerous economic and mechanical advantages, such as uniform stress distribution and the ability to join dissimilar materials . However, these potential benefits are tempered by a lack of confidence among designers in the long-term durability of bonded assemblies under repetitive thermomechanical stresses . Therefore, a deeper understanding of the durability characteristics of bonded composite assemblies is essential for their broader application in the transport industry. Composite structures are susceptible to accidental impacts during their use, as well as during fabrication and maintenance, such as tool drops and mishandling . One of the most practical solutions for repairing composite structures involves replacing the damaged area and bonding patches of varying sizes onto the surface of the structure. Bonding external patches is also widely used in repairing metal structures to halt defect propagation, and numerous studies have validated and standardized this repair method. Unfortunately, the repair of laminated composite structures through bonding external patches is much less documented and requires further investigation

2. Literature Review

This literature review examines the current state of research on repair techniques, the finite element method, fracture mechanics, and adhesive bonding techniques, highlighting their roles in enhancing the structural integrity and longevity of composite materials.

2.1 Repair Techniques

Repair techniques for composite materials have evolved significantly over the past few decades. Traditional methods such as mechanical fasteners have been largely replaced by more advanced techniques like bonded composite patches and adhesive bonding. These modern techniques offer advantages in terms of weight savings and improved stress distribution. Studies have shown that composite patches can effectively restore the load-bearing capacity of damaged structures, provided that the repair is properly designed and executed (Baker, 2003; Jones, 1998).

2.2 Finite Element Method (FEM)

The finite element method (FEM) is a powerful computational tool used to analyze the behavior of composite materials under various loading conditions. FEM allows for detailed simulation of stress and strain distributions, making it invaluable in the design and assessment of repair techniques. Researchers have used FEM to optimize the size, shape, and material properties of composite patches, as well as to study the effects of adhesive layer properties on the overall repair effectiveness (Ochoa & Reddy, 1992; Tong & Soutis, 2015).

2.3 Fracture Mechanics

Fracture mechanics is essential for understanding the failure mechanisms in composite materials. It provides a theoretical framework for predicting the initiation and propagation of cracks under various loading conditions. Studies have demonstrated that the placement and orientation of cracks significantly influence the performance of composite patches and that FEM can be used to predict these effects accurately (Kinloch, 1987; Abrate, 1998).

2.4 Adhesive Bonding Techniques

Adhesive bonding techniques have gained popularity due to their ability to create uniform stress distributions and their suitability for joining dissimilar materials. The effectiveness of adhesive bonds is influenced by factors such as surface preparation, adhesive selection, and environmental conditions. Research has shown that proper surface treatment and adhesive selection are critical for achieving strong and durable bonds (Adams et al., 1997; da Silva et al., 2011).

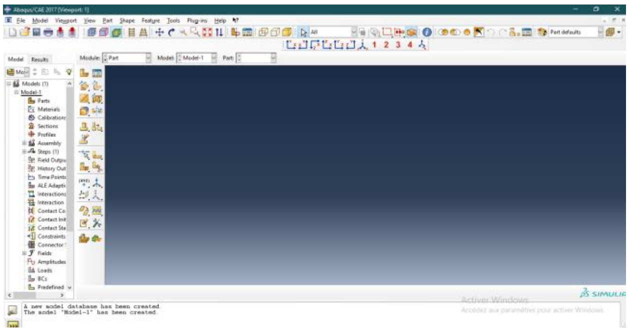
3. Methodology

The integration of FEM, fracture mechanics, and adhesive bonding techniques has led to significant advancements in repair strategies for composite materials. By combining these methodologies, researchers can design and validate repair techniques that offer superior performance and durability. For instance, FEM can be used to model the stress distribution in a bonded repair, while fracture mechanics principles can help predict the growth of any residual cracks. Adhesive bonding techniques then ensure that the repair maintains its integrity under operational conditions

Figure 1 . Pipelines in enivrement

4. Simulation sous ABAQUS

ABAQUS is a finite element analysis software developed by ABAQUS, Inc. It consists of three products: ABAQUS/Standard, ABAQUS/Explicit, and ABAQUS/CAE. ABAQUS/Standard uses an implicit integration scheme for solving general problems, while ABAQUS/Explicit employs explicit integration schemes for solving nonlinear dynamic or quasi-static problems. ABAQUS/CAE is a modeling and visualization interface for the mentioned solvers. The software is written in C++, Fortran, and Python for scripting and parameter settings, with a graphical interface based on the FOX Toolkit. (shown figure 2)



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A new model database has been created.
The model "Model-1" has been created.
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Figure 2 : the ABAQUS windows

We will present the main modules of ABAQUS, considering the repair of a pipeline with a composite patch. The outer diameter of the pipeline is Do=620 mmDo=620mm and the inner diameter is Di=480 mmDi=480mm; the adhesive thickness is ec=0.15 mmec=0.15mm; the patch thickness is ep=4 mmep=4mm. The applied load and pressure are F=50 MPaF=50MPa and P=100 MPaP=100MPa. The following table shows the properties of the parts to be modeled. (Table 1)

Table 1. the properties of the parts to be modeled

	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)
Patch (carbone /époxyde)	150	25	25	0,21	0,21	0,21	7,2	5,5	5,5
Adhesive (FM73)	2,55			0,32					
Pipe (acier inoxydable SA312Type 304)	204			0,3					

5. Results and discussion

Crack repair on pipelines is an important aspect of the maintenance and upkeep of gas and liquid transportation networks. Current research focuses on developing reliable and effective repair methods to address this type of issue. This study presents a three-dimensional finite element analysis using the Abaqus software for complete cracks in pipelines repaired with carbon/epoxy patches. The pipeline is subjected to bending forces and pressure, giving an applied stress of σ=100 MPaσ=100MPa for pressure stress and F=50 MPaF=50MPa for bending stress, as shown in Figures3 and 4.

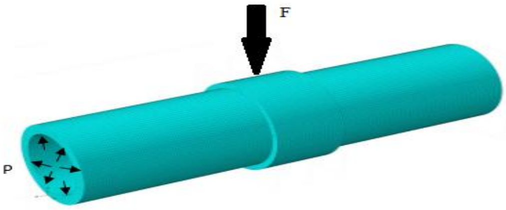

Figure 3: Pipeline repaired under 100 MPa pressure load plus 50 MPa flexural load

Figure 4 : Pipeline repaired under 100 MPa pressure load

The geometric characteristics of the cracked pipeline are:

Outer diameter D0=620 mmD_0 = 620 \, \text{mm}D0 =620mm

Inner diameter Di=480 mmD_i = 480 \, \text{mm}Di=480mm

Equivalent diameter Dm=550 mmD_m = 550 \, \text{mm}Dm =550mm

The crack size is represented with the angle θθ. The pipeline is made of stainless steel SA 312 type 304. The repair patch is bonded to the pipeline with FM73 structural adhesive. Table 1 provides the elastic properties of the pipeline, patch, and adhesive.

The study involved a three-dimensional finite element method to complete and analyze tests using the commercially available Abaqus finite element code. The finite element model consists of three parts to model the cracked pipeline, adhesive, and composite patch. The model comprises eight brick elements with 49,553 nodes, having 65,689 nodes and a total of 104,876 degrees of freedom: 19,754 in the pipeline, 9,245 in the adhesive layer, and 7,986 in the patch sections.

Figure 5 shows the overall mesh of the sample, and Figure 6 presents the mesh refinement in the crack tip region. The stress intensity factor (SIF) at the crack tip was extracted using the Virtual Crack Closure Technique (VCCT). The VCCT criterion utilizes principles of Linear Elastic Fracture Mechanics (LEFM) and is therefore suitable for problems where brittle crack propagation occurs along predefined surfaces.

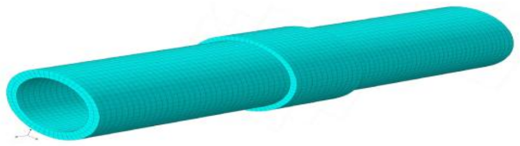

Figure 5 . Typical mailing model of the global structure

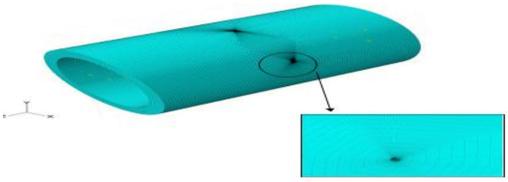

Figure 6 .Mailing model at the front of the fissure.

The stress intensity factor (SIF) at the crack tip was extracted using the virtual crack closure technique (VCCT). The VCCT criterion uses the principles of linear elastic fracture mechanics (LEFM) and, therefore, is appropriate for problems where brittle crack propagation occurs along predefined surfaces.

VCCT is based on the assumption that the strain energy released when a crack extends by a certain length is the same as that needed to close the crack by the same length. In this technique, the stress intensity factors are obtained for the three opening modes from the fracture equation:

$$G_i = \frac{K_i^2}{E} \qquad (1)$$

where GiG_iGi is the energy release rate for mode iii, KiK_iKi the stress intensity factor for mode iii, and EEE the modulus of elasticity. As the stress intensity factor increases, the energy at the crack tip also increases, leading to greater crack growth, which reduces the residual life of the structure. The residual life of the pipeline is defined from crack initiation to the critical crack length that requires the damaged pipeline to be replaced.

We will try to illustrate this effect numerically by studying the variation of the JJ-integral during crack propagation. The JJ-integral (curvilinear integral) represents a way to calculate the strain energy release rate or work (energy) per unit area of the fractured zone within a material. The theoretical concept of the JJ-integral was developed independently in 1967 by Cherepanov and in 1968 by Jim Rice. These studies highlight that the contour defining the plastic zone near the crack front (called JJ) is independent of the crack profile (contour). In this paragraph, we will determine the evolution of this integral as a function of crack length for repaired and unrepaired specimens. We calculated the difference in the JJ-integral between the maximum and minimum stresses:

$$\Delta J = J_{max} - J_{min} \qquad (2)$$

The SIFs KIKI, KIIKII, and KIIIKIII correspond to modes I, II, and III of crack propagation, respectively, generally used in FEM to characterize the stress and displacement fields of the crack and the placement fields. They are related to the energy release rate (JJ-integral) through:

$$G=\frac{1}{8\pi} K^T B^{-1} K \qquad (3)$$

where K=[KI,KII,KIII]TK=[KI,KII,KIII]T are the SIFs, and BB is called the pre-logarithmic energy factor. For homogeneous and isotropic materials, BB is diagonal, and the equation above simplifies : to:

$$\text{to: } G=\frac{1}{E}\left(K_I^2 + K_{II}^2\right) + \frac{1}{2G} K_{III}^2 \qquad (4)$$

The JJ-integral is a measure of strain energy in a material, used to evaluate the energy release rate for plane crack propagation. It is often used in fracture mechanics to analyze cracks and material failures. Energy methods involve using the JJ-integral for ductile fracture analysis and calculating the energy released during crack propagation in 3D materials.

Calculations of the JJ-integral were performed for repaired and unrepaired cracks in pressurized pipes to estimate the repair performance. The figure below shows the variation of JJ for repaired and unrepaired cracks at the vertical position of the crack front for different crack sizes. A significant reduction in JJ is observed. For example, for a crack length of 30 mm, the reduction rate of JJ is about 81%, and an asymptote is observed.

The variation of JJ for the horizontally repaired crack demonstrates the good effectiveness of the wrap-around repair method. This good effectiveness is also noted for metal patches used to repair pipes subjected to pressure loads. According to the figure, for the repaired crack, JJ shows an asymptotic behavior as the crack length increases. This is due to stress transfer between the repaired pipe and the wrap-around patch through the adhesive layer.

This reduction is due to the absorption of stresses by the composite patch. The stress reduction around the crack tip significantly lowers the JJ-integral values. This reduction will, of course, depend on several parameters, including the mechanical properties of the patch, its geometric properties, the properties of the adhesive, and the level of loading.

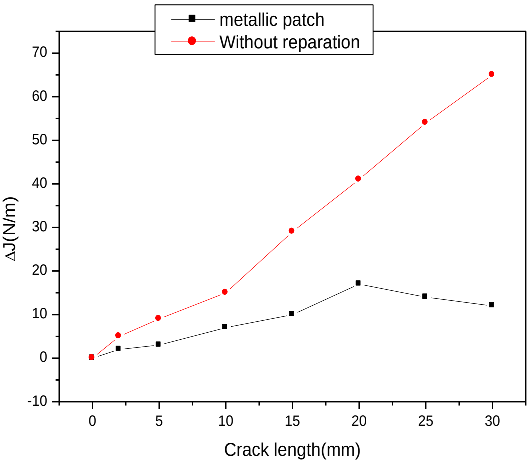

Figure 7 : Comparison of the variation of the Integral J for a pipe repaired by a metal patch and not repaired horizontally fissured under a pressure of 100 MPa

According to Figure 7, the curve retains its asymptotic shape, with internal stresses increasing compared to the stresses in the presence of a horizontal crack by about 10%, making the most favorable case a vertical crack. For this reason, we decided to complete all remaining studies with the presence of a vertical crac

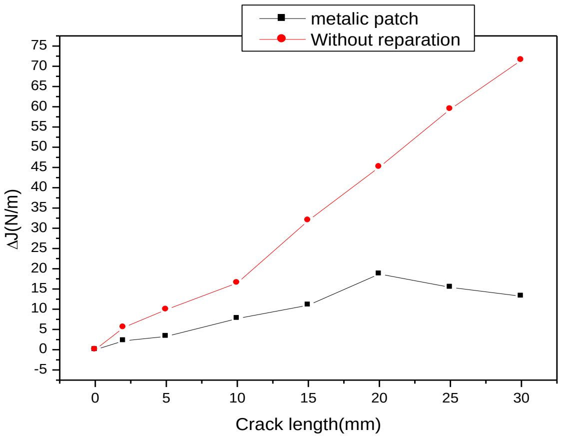

Figure 8 : Comparison of the variation of the Integral J for a pipe repaired by a metal patch and not repaired vertically fissured under a pressure of 100 Mpa

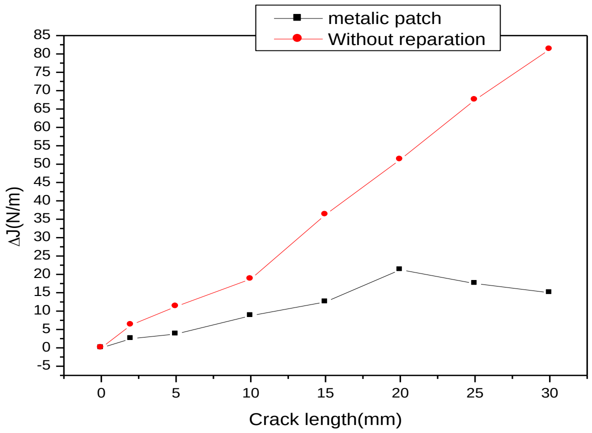

Figure 9 shows the variation of the JJ-integral as a function of crack length by comparing the variation for a pipeline repaired with a metal patch and an unrepaired vertically cracked pipe under a 100 MPa pressure load and a 50 MPa bending load.

According to Figure 72, the metal patch significantly influences the JJ-integral variation. For a crack length of 20 mm, the JJ-integral variation is about 52%. This behavior may be due to the significant stress transfer through the adhesive layer in the presence of the patch. The presence of the bending load increases the stress concentration by about 14%.

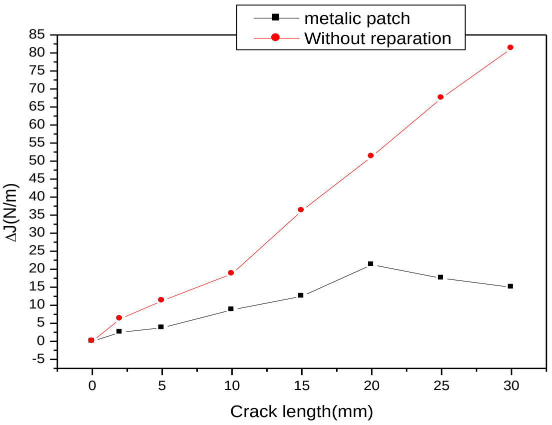

Figure 9 Comparison of the variation of the Integral J for a pipe repaired by a metal patch and not repaired vertically fissured under a pressure charge of 100 MPa plus a flexural charge of 50 Mpa

6. Study of Fiber Orientation Effect

It is recommended in composite patch repair that fiber orientation be studied to find the optimal orientation and avoid increased stresses. Figure 10 describes the variation of the JJJ-integral as a function of composite fiber orientation for vertical crack positions under a 100 MPa pressure load and a 50 MPa bending load. The difference in the JJJ-integral between 0°, 45°, and 90° orientations decreases proportionally with increasing crack size up to 20 mm and then stabilizes. The 45° fiber orientation presents the ideal orientation for a pipeline repaired with a composite patch and vertically cracked under a 100 MPa pressure load and a 50 MP

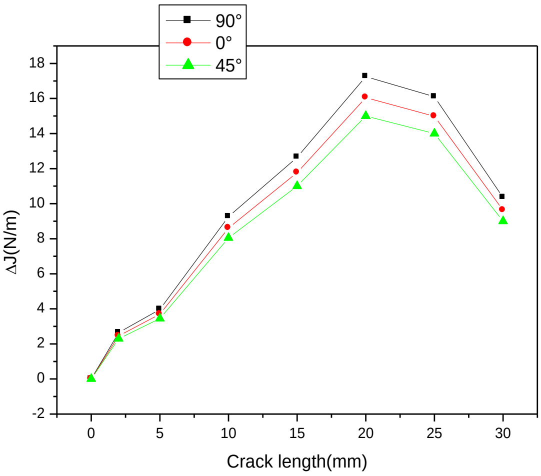

Figure 10. Etude of the fiber orientation effect for a pipe repaired by a composite patch and not repaired vertically fissured under a pressure charge 100 MPa plus 50MPa flexural load

Figure 11 describes the variation of the JJ-integral as a function of composite fiber orientation for vertical crack positions under a 100 MPa pressure load. The difference in the JJ-integral between 0°, 45°, and 90° orientations decreases proportionally with increasing crack size up to 20 mm and then stabilizes. The 0° fiber orientation presents the ideal orientation for a pipeline repaired with a composite patch vertically cracked under a 100 MPa pressure load, benefiting from pressure diffusion from the pressure direction and due to the presence of a vertical crack (the fiber direction perpendicular to the vertical expansion direction of the crack).

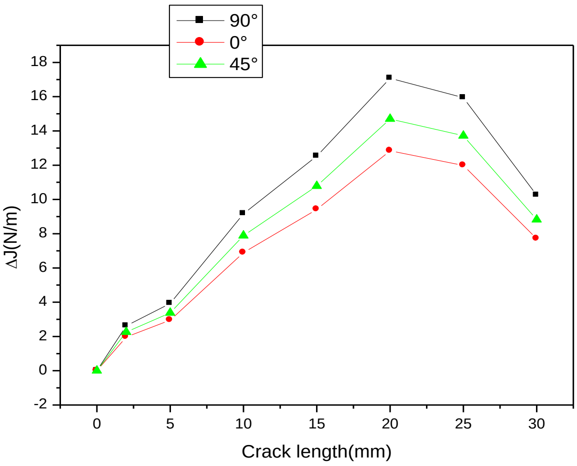

Figure 11 . Etude of fibre orientation effect for Pipeline repaired by vertically fractured composite patch under 100MPa flexural load

7. Comparison between Metal Patch and Composite Patch Repair

The nature of the patch is a determining parameter in repair behavior. Figure 12 shows the variations of the JJ-integral for pipelines repaired with a metal patch and a composite patch vertically cracked under a 100 MPa pressure load for different patch types (metal patch, composite patch with 45° fiber orientation). According to Figure 75, the composite patch provides lower JJ-integral values compared to the plate repaired with a metal patch. It is also noted that the efficiency of the composite patch is remarkable from a crack size of 15 mm onwards.

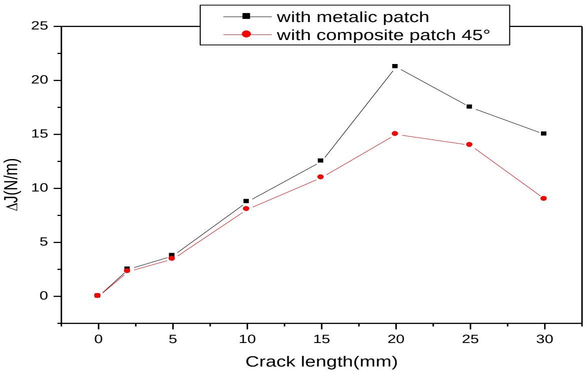

Figure 12 Comparison of variation of Integral J for Pipeline repaired by metal patch and repaired by vertically fissured composite patch under 100MPa pressure load

From the results in Figure 13, we can observe that the increasing JJ-integral of the metal patch is higher than that of the composite patch with a 45° fiber orientation for pipelines repaired with a vertically cracked under a 100 MPa pressure load and a 50 MPa bending load. This superiority holds for all crack lengths. This difference is due to the higher stress absorption rate for a metal patch. This difference is consistent with the results obtained in the first case (vertically cracked pipeline under a 100 MPa pressure load)

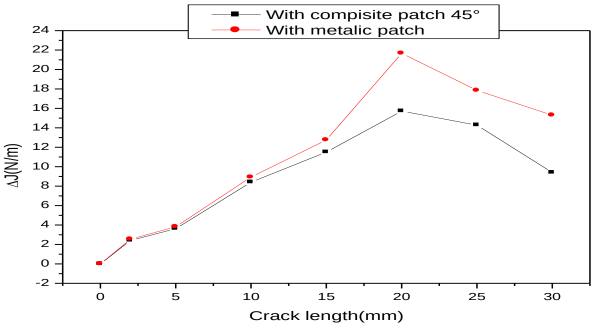

Figure 13: Comparison of variation of Integral J for Pipeline repaired by metal patch and repaired by vertically fissured composite patch under 100 MPa pressure load plus 50 MPa flexural load

7. CONCLUSIONS

This study aimed to analyze the effects of pipeline repair on horizontal and vertical damage using different repair techniques, including metallic patches and composite patches with various fiber orientations. It has been demonstrated that crack propagation is highly dependent on the ductility of the repaired material. This dependency remains significant even after applying a composite patch. The use of RPC (Reinforced Polymer Composite) significantly increases fatigue life and reduces stress concentration by approximately 81% when using a metallic patch.

Vertical cracking poses a greater risk compared to horizontal cracking, making it more dangerous. The fiber orientation in composite patches has a notable effect on reducing stress concentration. A 45° fiber orientation is ideal for pipelines repaired with composite patches under vertical cracking subjected to a 100 MPa pressure load combined with a 50 MPa bending load. In contrast, a 0° fiber orientation is optimal for vertically cracked pipelines under a 100 MPa pressure load, benefiting from pressure diffusion in the direction of the pressure and the presence of a vertical crack.

The nature of the patch is a critical parameter in determining repair performance. Composite patches yield lower J-integral values compared to metallic patches. Additionally, the effectiveness of composite patches becomes remarkable for crack sizes of 15 mm or more under both loading conditions (100 MPa pressure load, and combined 100 MPa pressure plus 50 MPa bending load).

REFERENCES

Baker, A. A., (2003) "Bonded Composite Repair of Metallic Aircraft Structure," Kluwer Academic Publishers.

Jones, R. M., "Mechanics of Composite Materials," McGraw-Hill, 1998.

Ochoa, O. O.,and Reddy, J. N., (1992) "Finite Element Analysis of Composite Laminates," Springer.

Tong, L., and Soutis, C., (2015) "Recent Advances in Structural Joints and Repairs for Composite Materials," Springer.

Kinloch, A. J., (1987)"Adhesion and Adhesives: Science and Technology," Chapman & Hall.

Abrate, S.,(1998) "Impact on Composite Structures," Cambridge University Press,.

Adams, R. D.,(1997) Comyn, J., and Wake, W. C., "Structural Adhesive Joints in Engineering," Springer.

da Silva, L. F. M.,(2011) Öchsner, A., and Adams, R. D., "Handbook of Adhesion Technology," Springer.

Wang, J., Zhang, Y. and Li, H. (2021) "Finite element analysis of the performance of composite repairs on damaged pipelines", Composite Structures, Vol. 256, pp. 113015. [DOI](https://doi.org/10.1016/j.compstruct.2020.113015)

Brown, A., Zafar, M. and Hoa, S.V. (2020) "Impact of fiber orientation on the effectiveness of composite patch repairs for pipeline defects", Journal of Composite Materials, Vol. 54 No. 24, pp. 3753-3766.

[DOI] (https://doi.org/10.1177/0021998320910568).

Smith, C., Nguyen, L. and Anderson, T. (2022) "Evaluation of adhesive properties for composite patch repair of pipelines using finite element methods", International Journal of Adhesion and Adhesives, Vol. 113, pp. 103056. [DOI](https://doi.org/10.1016/j.ijadhadh.2022.10305