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Review

Review of Piezoelectric Actuator Applications in Damaged Structures: Challenges and Opportunities

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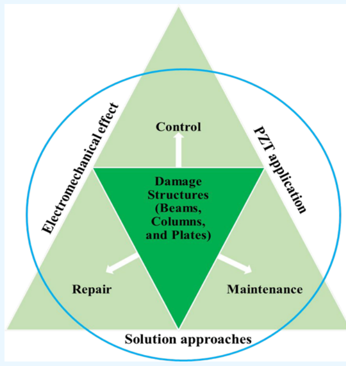
ABSTRACT: Piezoelectric material transducers can work as an actuator or sensor. Generally, the actuator will be used to repair the structure, and the sensor will be used to find the health condition. In the last two decades, piezoelectric actuators have shown the capacity to lower and control the shear stress concentration and joint edge peel in adhesively bonded joint systems. Hence, this paper aims at reviewing the application of piezoelectric actuators in damaged structures and adhesively bonded combined systems based on three different repair investigation methods: analytical, numerical, and experimental. Moreover, the study also explores the delamination control of composite material beams and some other studies using a piezoelectric actuator. The specific aim of this work is to determine scientific challenges and future opportunities for considering piezoelectric materials in damaged structure investigations for novice researchers.



1. INTRODUCTION

Fracture mechanics is the study of mechanical behavior in a cracked material subjected to an applied load. Brittle fracture is a low-energy process that fails without warning due to high crack velocity and no plastic deformation, whereas ductile fracture is a high-energy process with a large plastic deformation before crack instability occurs.[1] A crack in a material or a body may occur due to three distinct types of propagation such as opening, shearing, and tearing which involve displacements of the crack surfaces. Figure 1 shows the fracture modes. The mechanical behavior of a solid containing a crack of a specific geometry and size can be predicted by evaluating the stress intensity factors K_I (mode I), K_{II} (mode II), and K_{III} (mode III).[1] For example, when external loads are affected by a body, there is a chance of material failure.

Because of this, numerous studies have focused on the application of smart material's direction in the structural repair of damaged or cracked materials. The most characteristic examples of smart materials are shape memory alloys and piezoelectric materials which are broadly used in various engineering applications. In this review, the focus is on the piezoelectric material application in fracture mechanics problems. The piezoelectric materials have been characterized by the electromechanical effect which is the advantage of using electrical and mechanical studies. The piezoelectric sensor, actuator, and integrated transducer can sense the crack in different types of structures like thin plates, beams, tubes, and columns with reasonable accuracy. Previous studies noticed that piezoelectric materials have extraordinary sensing and existing capacity.[2] Later, Prasad et al.[3] stated the criteria for the evaluation and selection of piezoelectric actuator configuration for the different applications of smart structures with emphasis on shape and vibration control.

In such studies, Lee et al.[4] reported that the delamination and repair of a damaged structure with the use of piezoelectric actuators and sensors by considering the theoretical and analytical solutions was found to be an effective method to control delamination. Another important fact was reported by Sohn et al.[5] who developed a novel method for signal processing techniques to predict delamination in composite plates. This has become a key finding in delaminated composite materials considering the shell type of structures. Wang et al.[6] used piezoelectric materials to control delamination and avoid fractures in composite beams. The authors concluded that sufficient voltage is required to control the delamination of the beam, which depends purely on the location of the delamination. A similar study was done for the repair of a delamination beam using piezoelectric patches through the ANSYS simulation by Liu.[7] This study suggested that lower voltage is suitable for safer operations and is economical as well. Also, the patch length, thickness, and layer considerably affect the design of the piezoelectric patch. Iannucci et al.[8] investigated the possibilities of using

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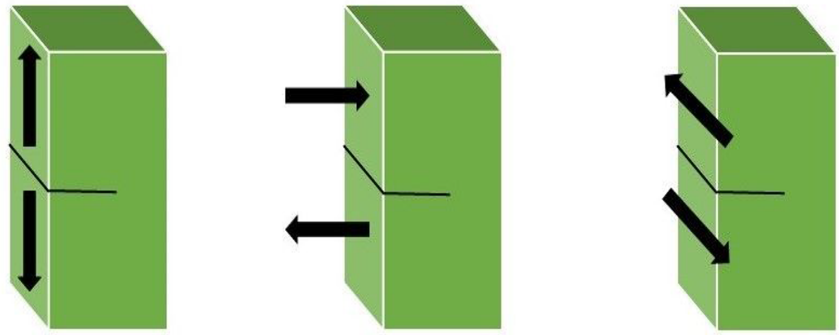

Figure 1. Stress-loading modes.

piezoelectric patches for the control of delamination in composite beams, subjected to a low-velocity impact. Wang et al.[9] quantified the smart materials that have been employed in the applications of structural repair because of their adjustable mechanical properties. Several studies have been conducted on delamination control, vibration control, and noise control by Aabid et al.[10] Also, PZT was utilized for energy-harvesting purposes,[11,12] but a lack of investigations was found on the repair of aircraft structures. So, this work aims to elaborate on ideas and work on research gaps in previous work. The first studies were conducted by Abuzaid et al.,[13,14] and they studied the electromechanical response in active repair and the control of the damaged structure. They found that the piezoelectric actuator can repair the thin plates at lower shear stress concentration and control the joint edge peel in the adhesive-bonded joint system. The authors proved that the effect of adhesive bonds on an active repair is to transmit the induced stresses by the piezoelectric actuator patch to the cracked plate in order to reduce the stress intensity factor (SIF).

The objective of this review is to attend to the use of a piezoelectric actuator for the repair of the damaged structure and delamination control using the adhesive-bonded system in distinct types of structural materials. The piezoelectric materials/constitution equation and their fundamental study are presented in the next section. Section 3 is divided in terms of three solution methods: analytical, numerical, and experimental repair methods. In the analytical section, our first documentation is based on fracture mechanics and its modified equations with the different boundary conditions in order to investigate the damaged structure and then repair the mechanism using piezoelectric actuator patches. Next, the following two subsections will discuss the piezoelectric patch applications in the active repair of damaged isotropic material type of structures and the delamination of orthotropic material type of structuress in terms of numerical and experimental work. Section 4 has a discussion of the present challenges and opportunities for future research in this area of interest. Finally, a conclusion has been made based on the present review work.

2. PIEZOELECTRIC MATERIALS AND ITS TYPES

Piezoelectric materials are the materials that produce a voltage when stress is applied. In other words, stress within the sample can be produced when a voltage across the sample is applied. Because of their diverse applications in different structures, piezoelectric actuators come in a variety of shapes and sizes, including patches, thin films, stack cylinders, and fibers, and may be used in a variety of designs.[9,15] Currently, the types of piezoelectric materials that are available in automotive and aerospace engineering are:

1. Lead Zirconate Titanate (PZT)[16−18]
2. Lead Titanate (LT)[19]
3. Sodium Potassium Niobate (SPN)[20]
4. Lead Magnesium Niobate (PMN)[21]
5. Lead Meta Niobate (LMN)[22]

Apart from these types of piezoelectric materials, Lead Zirconate Titanate (PZT) is one of the most frequently studied ferroelectric materials because of its extremely wide field of applications as a pyroelectric material. This material is widely used for repairing structures, and it is one of the most important materials used in industrial applications due to its superior performance. PZT is used for repairing cracks, shape control, vibration control, structural health monitoring, etc. The constitutive equations describe the PZT properties assuming that the total strain in the transducer is the sum of mechanical strain induced by the mechanical stress and the controllable actuation strain caused by the applied electric voltage.[16] Badr et al.[18] and Wang et al.[23] identified the effect of a PZT actuator for the simply supported beam and developed the relationship between the voltage and parameters and the interface of material properties between the beam and PZT layer.

Nonlinear dielectric, elastic, and PZT relationships in PZT ceramics were described well in PZT constitution equations as well as Preisach-type models, which have been hired to define the hysteretic path-dependent strain−field relationship in the PZT actuator.[24] Hudec[25] analyzed the monomorph (also called unimorph) PZT plate. PZT materials are capable of actuation and sensing, and they have been used in an extensive diversity of smart devices and structures.[26] Inoue et al.[27] analyzed the effects of increasing the thickness of the PZT bimorph structure in some double-coated layers of thin films. The thick PZT films allow high-voltage application and large generative force, which are effective in microelectromechanical system (MEMS) applications. The above investigation was important to learn that a lot of research has been done on PZT itself. Later this PZT was employed in fracture mechanics which can be seen in Section 3 of this review.

2.1. Effect of the Piezoelectric Actuator. A piezoelectric material actuator creates an electric field in response to the external load, and equally, the mechanical deformation will be generated when the electric field is applied.[28,29] Piezoelectric devices have become key mechanisms in smart actuator

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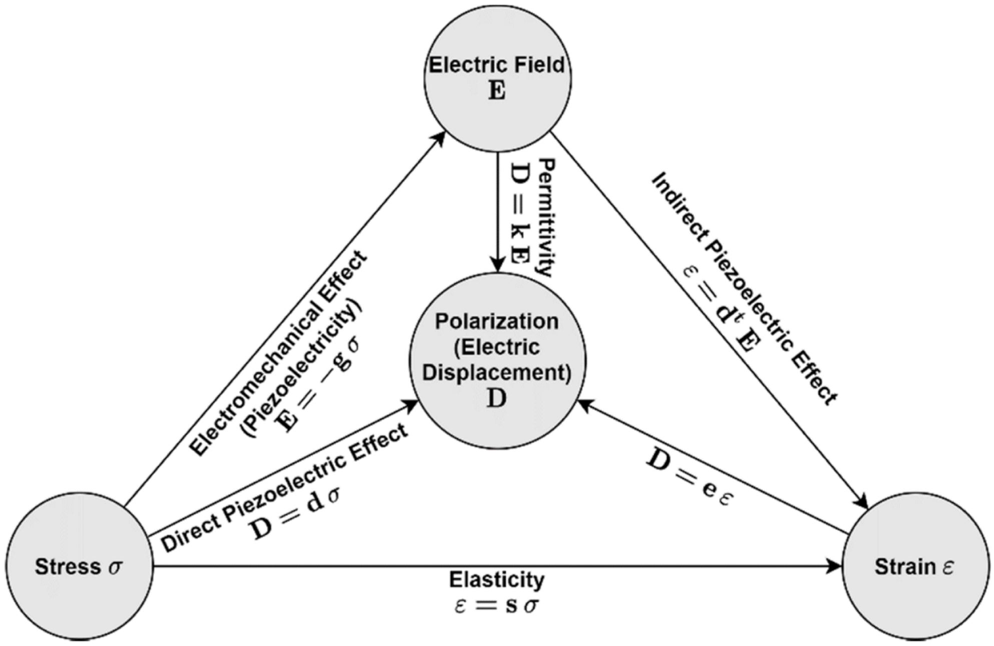

Figure 2. Effect of piezoelectric material.[10] Reprinted under the Creative Commons (CC) License (CC BY 4.0).

systems because of their electromechanical effect. The piezoelectric and related actuators focus on the improvement of actuator materials, shape, design, structure, and applications.[30] Yoichi et al.[31] planned to supply actuators of numerous sizes and thus contribute to technical innovations in the manufacturing industry in various areas. The piezoelectric materials are used to produce voltage when the load is applied. This effect is also used in a reverse manner. However, suitably designed structures are made from these materials, therefore, that bend, expand, or contract when a voltage is applied. Figure 2 shows the effect of piezoelectric material.

2.2. Piezoelectric−Mechanical Constitutive Equations. Under the effect of voltage and stresses, resulting strain and charge collected by piezoelectric material command the sensing and actuation characteristics of such materials. For the actuator, the linear coupled piezoelectric−mechanical constitutive relation is

$$\{S\} = [c^{E}]\{T\} - [d]\{E\} \tag{1}$$

in which $\{T\}$, $\{S\}$, $\{E\}$, $[c]$, and $[d]$ are, respectively, the stress, strain, and electric field intensity and the elastic compliance and piezoelectric constant matrices. The superscript E means that the compliance matrix is evaluated at a constant electric field. For the piezoelectric actuator and beam coupling system, the coupled governing equations can be expressed as[32]

$$[M]\{\ddot{d}\} + [K]\{d\} - P[K_G]\{d\} = \{F\} + \{F_P\} \tag{2}$$

Here, $\{\ddot{d}\}$ is the generalized nodal displacement vector; $\{F_P\}$ is the actuator force vector; and $\{d\}$ is the piezoelectric strain constant. For sensor modeling of the simply supported beam, by the beam dynamic analysis theory, the normalized unforced dynamics are in modal form.[33] Depending on which side of the strain gauge the bonding is to, the system output vector is

$$V_0 = \begin{Bmatrix} V_{01} \\ V_{02} \end{Bmatrix} = \begin{Bmatrix} v_s\left(x = \dfrac{L}{5}\right) \\ v_s\left(x = \dfrac{3L}{5}\right) \end{Bmatrix} \tag{3}$$

where V_{02} and V_{01} are the voltages applied to the top and bottom piezo layers. Wang et al.[34] performed a piezoelectric actuator case study by considering the simply supported beam integrated piezoelectric actuator and gauges to show the effect of the constitution equation by liner coupled piezoelectric−mechanical relation.

2.3. Application of Piezoelectric Actuators. For structural actuation, piezoelectric actuators have long been known as simple, low-cost, lightweight, and easy-to-control smart materials. For the active repair, it has been observed from the literature study that PZT is used as the artificial piezoelectric actuator and has more advantageous characteristics of generating more electricity. It is effective for the repair of cracks and structural health monitoring. The piezoelectric actuators apply to different types of engineering applications for repair and manufacturing. The characteristic reaction of the piezoelectric material patches is referred to as "actuation" because the effect in turn can be a reshaping of the structure and motion outcome. The use of piezoelectric materials is specified in Figure 3. The information provided in Figure 3 is based on the current literature work and collects the particulars individually to define the percentage of each engineering application.

Abuzaid et al.[15] show the use of piezoelectric actuator patches for different specific applications like vibration control, shape control, noise control, structural health monitoring, active control, structural enhancement, energy harvesting, and control of stress in adhesive joints. Figure 4 shows the data and timeline associated with numerous areas of application in the background of piezoelectric actuators.

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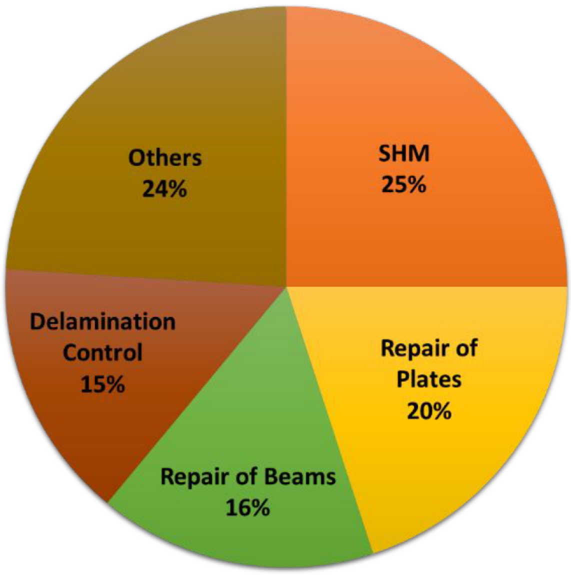

Figure 3. Piezoelectric actuators in engineering applications.

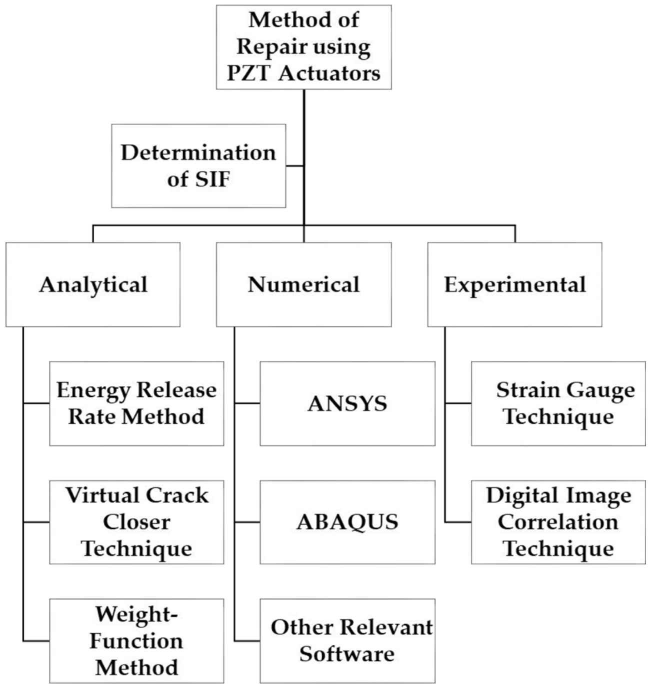

Figure 5. Types of active repair methods.

3. REPAIR/CONTROL METHODS IN FRACTURE MECHANICS STUDIES

In this paper, the methods which are used to repair damaged structures have been illustrated with three different results. Figure 5 shows the types of active repair methods for the repair of damaged structures.

3.1. Analytical/Mathematical Approach. In fracture mechanics (studies considering only crack without any external patches), the analytical approach proved the effect of plastic and elastic singularity by considering the triangular quarter-point element of the crack tip node. The singularity of elastic fracture mechanics and perfect plasticity denotes breaking one side and placing the midside node near the crack tip at the quarter-point.[35] In such cases, Dally et al.[36] developed the expression for the strain in the valid region to remove it from the crack tip by using strain gauges and accurately determined the SIF by numerical examples. Later, Gray et al.[37] considered 2D boundary integral fracture analysis and the standard singular element, and it was adjusted near the crack tip, opening displacement in order to obtain the accurate SIF. This analytical solution has been done for different mode conditions to define SIF and the improvement for the case of the mixed-mode conditions. However, these studies do not have any external effect to control the crack damages and improve the performance of damaged structures such as reducing the SIF, SCF, and J integral evaluations.

Later, Wang et al.[38] performed studies for the analytical relations in order to obtain the solution of buckling and the effect of crack on the buckling capacity of the damaged column. In their research, a small PZT patch was used to induce the local moments to compensate for the decreasing capacity of column structure by using the strain−voltage

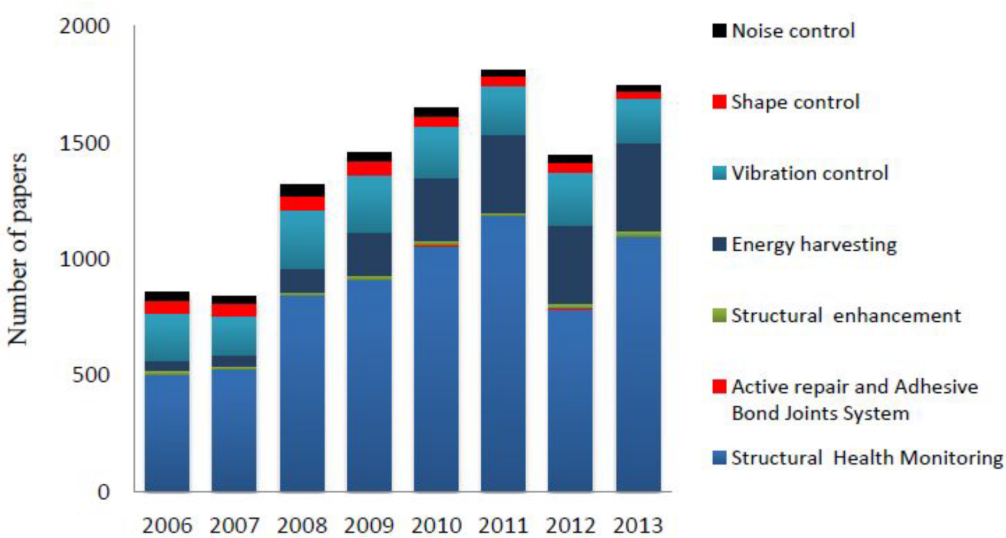

Figure 4. Research trends.[15] Reprinted under the Creative Commons (CC) License (CC BY 4.0).

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relation, and it was the first investigation that was able to reduce the column damage propagation. Then, Alaimo et al.[39] used the concept of PZT material actuators and repaired the damaged column structure when subjected to a different voltage of PZT actuators in reducing SIF for mode I crack propagation. Next, the authors developed a 2D boundary integral equation for PZT solids through a multidomain method to design the composite structure with the bonded PZT patches.[40] The same authors also presented the fracture mechanics behavior of delaminated composite structures by using the modified virtual crack closure integral technique, and it was implemented to characterize the fracture mechanics behavior of delamination beam in terms of energy release rate (ERR) and mixed-mode phase angle.[41] Later, they detected skin/stiffener debonding and delamination of the crack on the laminated composite structure using the PZT material.[42] Wang et al.[43] analytically modeled the behavior of a crack interface among the elastic substrate and PZT actuator by seeing the shear effect and the interface stresses for mode I and mode II energy release rates. Isaksson et al.[44] described the deformation of heterogeneous elastic materials better than the classical elasticity theory. They analytically formulated the relationship of stress/strain near the crack tip in the gradient method, and the geometry of the rigid body is shown in Figure 6.

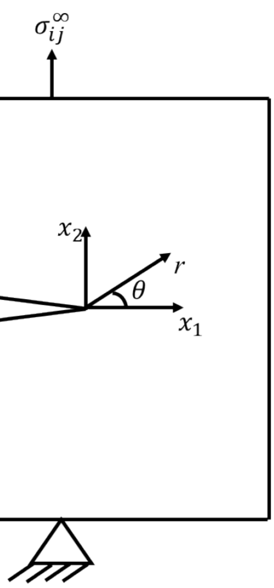

Figure 6. Load and geometry of the rigid body.[44] Copyright 2022. Reprinted with permission from Elsevier.

Cheng et al.[45] developed a smart joint to control the applied electric field of the PZT patch to reduce the stress concentration effect, forces, and bending moment at the edges. Next, the authors analyzed the smart composite pipe joint system to evaluate the function and efficiency of the integrated PZT layers and to calculate the effect of laminar thickness and applied electric fields on the peel and shear stress concentration.[46] Cheng et al.[47] performed another type of study on smart composite pipe joints using flexible PZT-reinforced polymer composites to improve the pipe joint strength and overcome the limitation of brittle PZT ceramic application. Rabinovitch[48] analytically studied the effect of mechanical and geometrical properties of the adhesive layer on coupled thin piezoceramic actuators, bonded to an elastic medium. Cheng et al.[49] formulated the joint pipe system subjected to the tensile load in a stress-transfer model of an adhesively bonded PZT material and investigated the stress distribution of shearing stress in adhesive layers. Chen et al.[50] developed a smart novel adhesive joint system, and a theoretical model was established to analyze the single-strap adhesive joint system. Khalili et al.[51] developed a single lap joint to control the force and bending moment at the edges of the model by surface bonding of PZT patches, thus reducing the peel and shear stress concentration effect.

Jin et al.[52,53] studied the partial performance of debonded adhesive layers on the coupled electromechanical behavior of PZT patches subjected to a low-frequency electric load. The adhesive layer which undergoes shear deformation is proposed to simulate the 2D electromechanical system, the effect of interfacial debonding on the dynamic response of the layered structure, and the interlaminar stress and strain transfer mechanisms. Abuzaid et al.[54] evaluated the reduction of SIF with bonded PZT actuators into a cracked plate using the weight-function method as anticipated by Bueckner.[55] The weight-function method depends not only on the stress distribution but rather on the structure geometry. Using the weight function, the SIF can be calculated using the PZT stress σ_{piezo}; therefore, the equation becomes

$$K_{\text{I(piezo)}} = \int_{\Gamma_c} \sigma_{\text{piezo}} h(x,\, a)\mathrm{d}x \tag{4}$$

where $h(x,a)$ is the weight function and Γ is the perimeter of the body, and it can be illustrated as

$$h(x,\, y,\, a) = \frac{\acute{E} du_y}{2K_\text{I} da} \tag{5}$$

where $\acute{E}$ is Young's modulus in either plane strain or plane stress conditions and K_I is the SIF for uniform tensile stress applied on the panel.

3.1.1. Repair of a Cracked Beam. Alfano et al.[56] determined the energy release rate of single-mode and mixed-mode delamination ($G = G1 + G2$) from different fracture mechanics equations. They also presented equations for double cantilever beam specimens and the problem involving the multidomain delamination energy release rates with sliding-mode equations

$$G_1 = \int_0^{\delta_1} t_1 \mathrm{d}\delta_1 \tag{6a}$$

$$G_2 = \int_0^{\delta_2} t_2 \mathrm{d}\delta_2 \tag{6b}$$

Narayana et al.[57] identified the active vibration control of the beam, plate, and shell-type of elements to integrate the stiffness, mass, and electromechanical coupling effect of the PZT laminates. They used the Timoshenko beam theory for the beam-to-shear deformation theory for the plate/shell, linear quadratic regulator (LQR) approach. Wang et al.[6] used a cantilever beam to demonstrate the repair method on the cracked beam under the dynamic load conditions by a PZT actuator. Zangeneh et al.[58] developed the spring model for the computational efficiency and effectiveness of delamination. The authors used the Reddy[59] layer-wise plate theory and energy release rate method to determine the buckling, postbuckling, and delamination propagation. Ariaei et al.[60] used Timoshenko beam theory and the application of PZT

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patches for the repair of moving mass cracked beams using mathematical modeling. Muthu et al.[61] analytically evaluated the mixed-mode SIF from the energy release rate of the crack using a nonhomogenous material plate specimen by using different element-free Galerkin methods and evaluated T-stress and the kinking angle at the crack tip.

Platz et al.[62] determined the cyclic stress intensity factor ΔK of a cracked thin panel structure by active induction of compression stresses into the crack tip area with the PZT actuator to the panel's surface near the crack tip. Al-Ashtari[63] used a novel analytical model to calculate the proper dimension of PZT patches. Different PZT patches were designed based on thickness, length, and shape using an analytical model. Referring to Figure 7, the slope of the repaired beam can be expressed as θ_r, and deflection of the repaired beam can be expressed as y_r. The governing equation of the repaired beam is

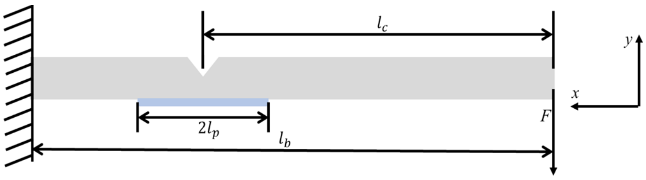

Figure 7. Cracked cantilever beam repaired with a PZT patch.[63] Reprinted under the Creative Commons (CC) License (CC BY 4.0).

$$Y_b I_b \frac{d^2 y_{r1}}{dx^2} = -Fx \quad 0 \le x \le l_c - l_p \tag{7}$$

Two effects can be caused by the PZT patch at the bonding location on the beam: increasing local stiffness and applying local bending moment. Finally, the constant introduced in the above equations k is defined as

$$k = \frac{Y_t I_t}{Y_b I_b} \tag{8}$$

As a result, increasing the patch thickness enhances the beam resistance to crack and load effects, while increasing the length of the PZT patches reduces the magnitude of the voltage required to repair the cracked beam.

Maleki and Mohammadi[64] used PZT patches to analytically investigate the stability of a cracked column made of a functionally graded material (FGM), and this was the first concept used in FGM materials. The crack location of the column connects the two intact parts by a rotational massless spring model of the crack. The governing equation of buckling was derived by applying the boundary and compatibility conditions at the crack of the column and identifying the effect of the crack, suggestively decreasing the buckling load of the column. To determine the impact of the fracture and the thickness of the piezoelectric layer on the structure's natural frequencies and the output charge caused by vibration modes, a modal analysis of a cracked beam with a piezoelectric layer was performed. The output charge associated with natural modes, known as the modal piezoelectric charge, is obtained by solving the governing equations of the coupled structure using the double beam model and two-spring (translational and rotational) description of the crack.[65]

3.1.2. Control of Delaminated Beam. Crawley et al.[66] presented a PZT actuator as an element of intelligent structures by analytical methods in terms of static and dynamic loads. They used a composite laminated cantilever beam and fixed it with the PZT actuator to derive each section. Garg et al.[67] introduced the delamination control on the laminated composite plate, which reduces the strength, stiffness, and life of the structure.

Predominantly, Coulomb's friction modeling approach was planned and first validated by the examination of a horizontal punch over an elastic substance.[68] The discontinuity of shear stress is induced at the two tips of the delamination, which may result in a sliding mode of fracture. Therefore, to simplify this type of problem, electromechanical characterization was used to remove the sliding mode of the fracture.[69] Alaimo et al.[42] investigated the sensing and actuating electromechanical performance of an adhesively bonded PZT plies in a bimorph device. Then, they actively repaired the drop-ply delaminated composite structure through a PZT multilayered patch by considering the frictional contact conditions. Wu et al.[70] developed the concept of a bonded PZT patch for delamination control in a laminated plate. In order to control the delamination, the PZT patches are bonded to the delaminated area. Amara et al.[71] evaluated the 32 layers of the laminated composite plate with a crack growth rate of delamination using the strain energy release rate method for the stress ratio effect.

Repair of the delaminated beam using PZT patches under static loading conditions was reported in 2008, and the repair voltage required at the bottom and top of the PZT patches depends on the delamination location.[72] Alaimo et al.[73] proposed a spring model to analyze the adhesive bonding effect on PZT patch performance which was used as an active repair for the cantilever beam. The voltage applied to close the crack increases with a reduction in the SIF. Alaimo et al.[39] performed another study using the boundary element method with the same PZT patches and studied the fracture mechanics of the delaminated surface. Repair of the delaminated surface was easily possible using this method, and their extensive study was on electromechanical behavior because of the adhesive bond between the composite and repair along with frictional contact. Again, they showed that the stiffness of the adhesive bond severely affects the behavior of PZT patches.[42] Another study during static loading conditions was reported by Wu, employing finite element method (FEM) analysis. They designed a discrete electrode to eliminate compressive and tensile forces around the delamination location. The voltages applied to the designed electrodes could repair the cracks by reducing stress singularity.[74]

Shah et al.[124] used the PZT ceramic to detect and suppress delamination in laminated composites by use of a quasi-three-dimensional FE model and developed the analytical model for a quasi-isotropic laminated plate with PZT layers. The defect on laminated crack was presented in detail by Bolotin,[75] and he studied aspects that concern delamination and other inter-laminar crack defects in a composite structure using the Pagano[76] concept. Wang et al.[23] repaired the delaminated plate using PZT patches subjected to tension and compression load distribution. The authors applied the voltage on the PZT electrodes in order to generate shear forces between the delaminated plate and PZT patches so that the distributed tension and compression load can be reduced. The effect of shear force on the delaminated edges at the crack joints of the upper and lower layers has been studied, and the equation of

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the shear force between the PZT actuator and the metal substrate was given by Crawley and De Luis[66]

$$S = \frac{EHT}{\psi + \alpha}\Lambda \tag{9}$$

where

$$\psi = \frac{EH}{E_p h_1} \tag{10}$$

where S is the compressive force produced by piezoelectric actuators; E is the Young's modulus of the plate; H is the thickness of the plate; T is the distributed electrode width of the cracked plate; α is the coefficient that is dependent on the operation mode of the actuator; and Λ is the PZT strain given by

$$\Lambda = \frac{d_{31}}{t_p}V \tag{11}$$

in which V is the piezoelectric voltage, d_{31} the piezoelectric coefficient, and t_p the thickness of the piezoelectric patch.

3.1.3. Crack Closure Integral Technique. The crack closure integrals can be divided into two types: modified crack closure integral and virtual crack closure integral for numerical analysis. The numerical estimation of SIF and potential energy release rate (PERR) introduced a universal crack closure integral (UCCI) method for a cracked structure.[77] Fett[78] compiled SIF and weight functions in many cases for two-dimensional (2D) and three-dimensional (3D) models with numerical estimation. Saravanos and Heyliger[4] introduced a crack into a residual stress field by a modified J-integral definition, and the authors showed that the J-integral is equivalent to SIF under small-scale conditions. The standard definition of J-integral leads to a path-dependent value in the presence of residual stress and numerical modeling of residual crack problems introduced in the field of FEM. Figure 8 illustrates the counter integral path and domain around the crack tip.

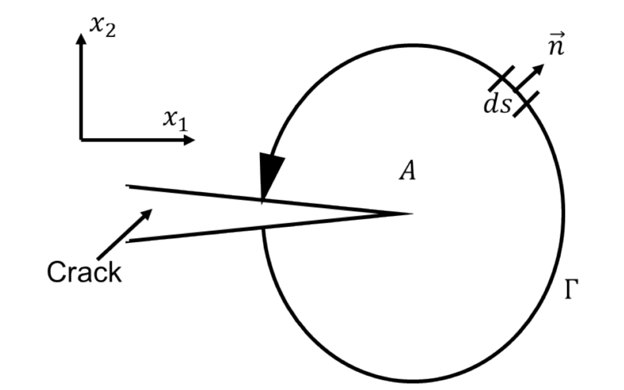

Figure 8. Counter integral path, Γ, and domain, *A*, around the crack tip.

For a 2D body with a crack directed along the x_1 axis under quasi-static conditions, a general equation of the J-integral[79] is given by

$$J = \lim_{\Gamma \to 0} \int_{\Gamma} \left(W\delta_{1i} - \sigma_{ij}\frac{\partial u_i}{\partial x_1} \right) n_i \mathrm{d}s \tag{12}$$

SIF is calculated by the linear elastic fracture mechanics (LEFM) method, such as weight function[80] or superposition method,[81] and converted to the J-integral via a given relation[79]

$$J = \frac{k^2}{E}(1 - \nu^2) \tag{13}$$

A detailed study was carried out by Krueger,[82] and analytical solutions for 2D and 3D solid elements as well as plate/shell elements with different approaches and their applications were considered. Liu et al.[83] calculated the energy release rate for the crack propagation with delamination growth by the virtual crack closure technique (VCCT). The energy release rate due to crack propagation on the crack closer surface is calculated as[82]

$$G = \frac{1}{2S}[F_{ix}\Delta u_{ix} + F_{iy}\Delta u_{iy} + F_{iz}\Delta u_{iz}] \tag{14}$$

Next, the fracture parameter Ψ descends to open the mix-moded angle of the phase, whose calculation is also obligatory for bimaterial edge fracture mechanics. Subsequently, the total ERR by itself does not permit the investigation of the critical conditions.[84] Therefore, the mixed-mode angle of phase computed under the assumption of insignificant oscillatory behavior of stress at the front of the crack and fields of displacement[85] through the ERR mechanisms is given as

$$\psi = \tan^{-1}\left(\sqrt{\frac{G_{II}}{G_I}}\right) \tag{15}$$

There are always advantages and disadvantages of any method/object. Hence, some of the important terms based on the exciting analytical work of this review have been provided.

3.2. Numerical Simulations. Another widely used method is the finite element (FE) method. The FE method applies to all disciplines of engineering solutions. This paper reviewed the FE method based on the active repair method using PZT patches. A number of tools are available to simplify the FE method in engineering applications. For the determination of structural solutions, the most recent research work has been done through ANSYS and ABAQUS commercial software which have predominant solutions in the simulation. It has been observed that ANSYS software was most widely used for simulation and validation purposes in recent years.

In an early investigation on fracture mechanics, Chan et al.[86] numerically calculated the SIF on a crack tip in the plate by compact tension and rotating test specimens. Rybicki and Kanninen[87] estimated the SIF for mode I and mode II of a single analysis with a constant strain and stress analysis using the FE method and simulated for a double cantilever beam (DCB) test specimen. Providakis[88] investigated the repair method for the cracked structure under dynamic load using the electromechanical admittance approach (EMA). The author used the 3D FEM method to model a cantilever beam with the combination of two different healthy and cracked structures' admittance signatures in the specific frequency range. Caimmi et al.[89] performed a three-dimensional finite element analysis for the single fiber composite fracture test. The authors aim to determine the SIF as a significant consideration of the study along a crack front on different orientation stiffness ratios.

The LEFM method was used with the FE model for the isoperimetric element to calculate the SIF. The different

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material model, such as eight-noded quadratic elements, was used and compared with existing numerical results by Banks-Sills et al.[90] Pietropaoli et al.[91] studied the combined effect of the VCCT and the failure release approach for the inspection of growing delamination in the laminated composite structure. They obtained the energy release rate of each segment of the delaminated front for a stiffened panel with an embedded delamination load. The authors used ANSYS APDL to design the stiffened panel for the validation of the result. Wu et al.[92] built an FE model in ANSYS 10.0 to verify the feedback repair of the notched cantilever beam. The effect of strain energy release rate for mode I with VCCT was implemented through FE analysis.[93−95]

Platz et al.[62] identified the most suitable position to apply the PZT patches on the damaged plate to lower cyclic stress intensity near the tip of the crack by inducing compressive forces using the simulation method. Abuzaid et al.[13,96] identified the distribution of the nodal stresses in the vicinity of the crack front for the different ranges of adhesive shear modulus with the PZT actuator. Abuzaid et al.[97] performed another study with the modeling of PZT patches using the SOLID226 element, which is available in the ANSYS tool. The authors achieved the repair performance by the adhesively bonded PZT patches depending on the transfer of the shear and peel stress. They used the three-dimensional FE investigation to understand the effectiveness of adhesive properties on the active repair performance of damaged plates under mode I propagation. Figure 9 shows the FE model of bonded PZT actuators. Fesharaki et al.[98,99] used the particle swarm optimization (PSO) algorithm to simulate the best position of the PZT patch around the plate hole subjected to a tensile load and determined the maximum reduction of the stress concentration factor. Later, they examined the effect of PZT patch placement in a plate to decrease the stress concentration factor around the hole under tension load by changing the stiffness ratio for two different cases using patches around the hole which were attached to the left−right and top−bottom.

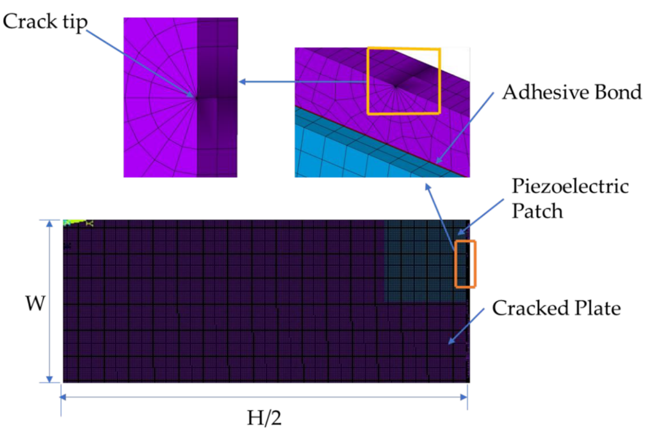

Figure 9. FE model of the bonded PZT actuator.

Aabid et al.[100] investigated the PZT patch effect in a center-holed plate with different repair configurations. Kumar et al.[101] considered the orthotropic composite plate as the host structure and did the repair by PZT actuators, and it was achieved through the FE method. As a result, the author illustrated the different voltage variations of contours. The efficacy of the repair is quantified in terms of SIF/J-integral, and the critical voltage at which patch repair is most successful is determined. In addition, the patch shape and dimensions were changed for effective repair under thermomechanical loading using the extended FE technique.[102] Analysis of three-dimensional cracks with different types of defects of piezoelectric materials has been modeled using the FE method to define the material stress, electric strength and displacement,[103] crack interaction,[104] and crack growth,[105] and characterization of in-plane piezoelectric actuators[106] was shown in different studies. A numerical study of smart structures with PZT actuators to enhance surface integrity has been shown to improve the toughness of the structure, and also the proper way of using the PZT actuators to delay the crack initiation under extreme loads was shown.[107]

3.2.1. Control of Delaminated Beams. The FE analysis of a delaminated beam subjected to static load with PZT-based active repair has been done through the moment equilibrium method to obtain the results using the ABAQUS software by Duan et al.[72]Figure 10 illustrates the mesh model and the boundary of the two separated layers through the delamination as two surfaces without saturation have been considered to model a beam. Special consideration was compensated to the finite element discretization of the tip of the crack, PZT patches, and contact interface.

Wu et al.[74] used a PZT patch to produce a local shear force on the delaminated part through an actuator voltage, which was intended as feedback for the vibrating beam deflection. In order to remove the singularity stresses near the tip of the delaminated beam, an FE method was used to confirm the projected design and repair method. Beam force is provided by eq 16[6]

$$F = \frac{EbH\beta}{2a}\left(\left.\frac{dw_L}{dx}\right|_{x=1} - \left.\frac{dw_R}{dx}\right|_{x=a+1}\right) \tag{16}$$

where $\beta = \frac{t(H-t)}{H}E$ is Young's modulus of the beam structure and w_L is the flexural deflection of the beam element at the left tip of the delamination area, while w_R is the flexural deflection of the beam element at the right tip of the delamination area.

Orifice et al.[108] developed the FE code named Marc 2008r1 to simulate delamination propagation in the composite material plate with the implementation of the VCCT method. Shindo et al.[109] used a PZT actuator to control the delamination in the woven glass fabric-reinforced polymer (CFRP) composite laminates subjected to the mode I load. The authors also investigated experimentally and numerically on the same material model with a bonded PZT actuator subjected to a mode I load under cryogenic temperature. The test was performed at 77 K of liquid nitrogen temperature.[110] Moreover, the SERR is calculated by considering the stress at the crack front and the displacements at the adjacent nodes. When the loads are static in a beam a study shows the repair and evaluated crack with and without PZT actuators using the Ritz and FE methods. They performed the evaluation and repair considering the different boundary conditions, and the results show the discontinuity in the curve slope which was developed due to a crack.[111]

3.3. Experimental Work. In this section, it has been observed that many researchers worked on the basic principle of PZT patches. A prototype material model such as a beam, plate, and column in order to test the specimen using available tools/machines was created. After benchmarking the results,

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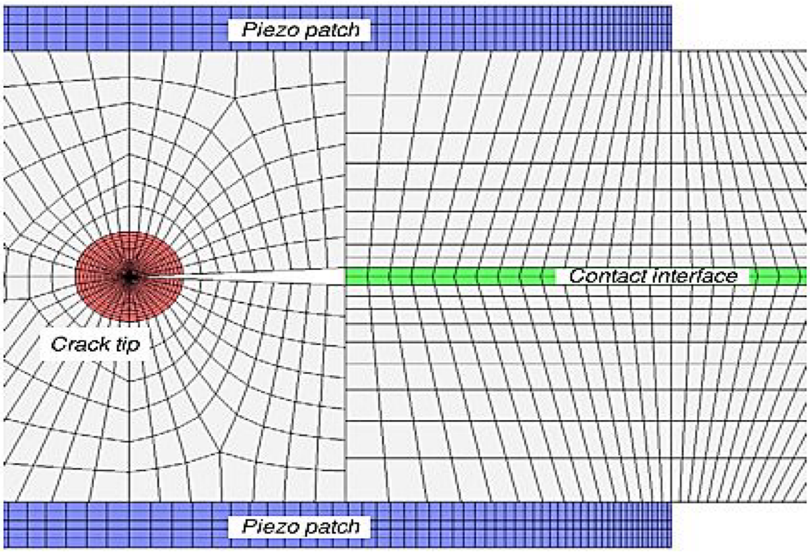

Figure 10. Finite element discretization.[72] Copyright 2022. Reprinted with permission from IOP Publishing.

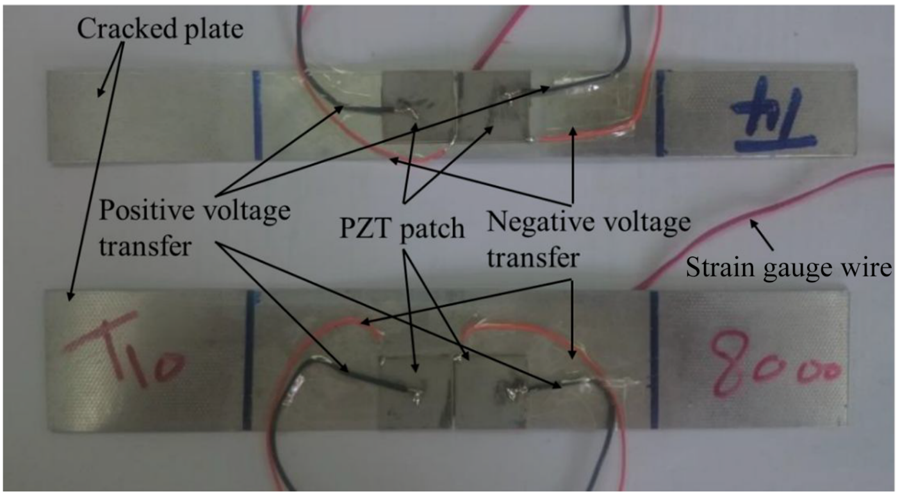

Figure 11. Edge crack plate integrated with the PZT patches.

validation with analytical and numerical studies is done. In addition, experimental results are significant to show the research output.

3.3.1. Active Repair of Isotropic Material Structures. Sarangi et al.[112,113] proposed the methodology for calculating the optimum strain gauge locations for measurement of the SIF by using the strain gauge technique in an aluminum plate. In order to get the optimum location, the authors used an FE technique with a different mesh model and evaluated elastic strain at the gauge line which is defined during the design of a plate. Younis and Kang[114] investigated the suitable selection of strain gauges for different measurements of required applications and the proper characteristics for the experimental work. They used dimensionless curves to estimate the errors and enhanced a hole-drilling method. Platz et al.[62] statistically evaluated the influence of controlled reinforcement on the crack tip by actively inducing mechanical compression forces near the tip of the crack to decrease the propagation of the crack.

Wu et al.[92] conducted the experiments to realize the effect of the PZT actuator bonded on notched cantilever beam repair under dynamic load and validated them with the analytical and FE results. Sarangi et al.[115] experimentally verified the optimal strain gauge locations and their importance in the accurate determination of mode I SIF using daily and Sanford's single-strain gauge training (DS technique). Abuzaid et al.[116] conducted the experimental work for the repair of the damaged plate (edge-cracked) with a bonded PZT actuator. To obtain the SIF for a mode I crack propagation, strain gauges were used. A typical plate integrated with PZT patches is shown in Figure 11. Later, Abuzaid et al.[117] validated the experimental results with an expressed analytical solution which was derived from the weight-function method. Fesharaki et al.[118] examined the best pattern for the enhancement of PZT actuators in a thin plate to reduce the stress concentration using the PSO algorithm. In order to obtain the results, an experimental test was conducted and later validated with numerical simulation. The authors show in the results for the placement of the PZT actuator that there is an influenced model at any convinced stiffness ratio in all standard plates.

Huynh et al.[119] established a PZT-based structure like a plate in order to monitor damage. They approached

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experimental and numerical solutions for depicting the sensing area of a PZT material boundary for monitoring damage in a structure like a plate. In recent work, the SIFs were determined for a cracked plate with bonded piezoelectric actuators under thermos-mechanical loading, and this has been the first study shown under such load effects. The authors have shown challenging results with different piezoelectric actuator voltages and reduced the SIFs. In addition, they have used multiple piezoelectric materials for sensing as well as actuating. Generally, the sensor will be utilized to measure the voltage and actuator to produce the forces to reduce SIFs.[102] Experiments were performed to determine the crack repair in a thin plate using PZT actuators.[120] The authors show the two cases of their studies considering mechanical loading and thermos-mechanical loading conditions and determined the SIF with and without PZT for the mode I crack. In most of the work, mode I crack propagation was the first choice of problem definition, and therefore Bujang et al.[121] focused on mode II and mixed-mode conditions to investigate the SIF and its reduction using PZT actuators. The results show a significant reduction in SIF with increasing PZT voltage under a certain limit (150 V), and other parametric studies were performed such as the effect of PZT thickness, size, actuator thickness, etc.

3.3.2. Delamination Control Using a Piezoelectric Actuator. Figure 12 shows the DCB specimens used for the description of interfaces in mode I and calculated the energy release rate.[122,123] The interfaces in question are bonded ones between the foam core and faceplates for the sandwich structures.[124] Ahmed et al.[125] placed laminates at the lower and upper end of the specimen at a distance of 50 mm from the front of the crack. The axis tab is made up of metallic material that can sustain the applied load without experiencing damage.

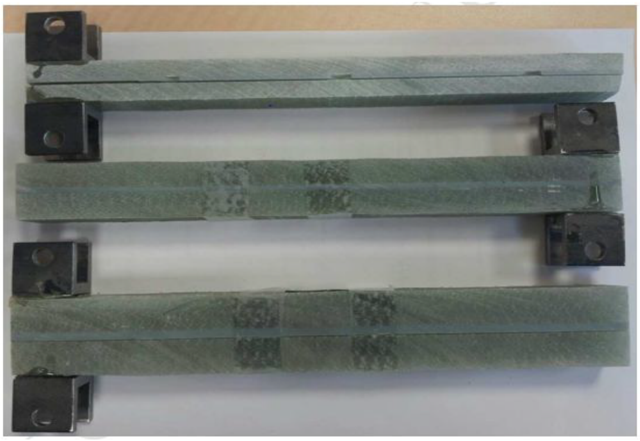

Figure 12. DCB specimen used for mode I fracture resistance tests.[124] Copyright 2022. Reprinted with permission from Elsevier.

3.3.3. Digital Image Correlation (DIC) in a Cracked Plate. To express more on experimental studies and to show the lack of PZT used to reduce the SIF and improve the damage performance, we did a literature survey on fracture mechanics in terms of LEFM and elastic−plastic fracture mechanics (EPFM) methods in order to determine the SIF using the Digital Image Correlation (DIC) method. From the previous studies, we found that DIC methods can exactly govern 2D and 3D strain fields and therefore seem well modified to afford the essential field data through SIF calculations.[126]

Hamam et al.[127] used the DIC technique to evaluate the SIF for a fatigue crack in a steel specimen. They observed that the SIF variation throughout one cycle is achieved using a decomposition of the displacement field onto a tailored set of elastic fields. Mogadpalli et al.[128] determined the SIF for a crack in orthotropic composite materials using the DIC technique. The authors extended the crack tip displacement fields, resulting from the current solutions for strain fields. Moreover, they considered an edge-cracked unidirectional fiber composite panel under remote tensile load, and the displacement was recorded using DIC. Richter-Trummer et al.[129] proposed a methodology for in situ SIF determination for the damaged structures using DIC combined with an over-determined algorithm. The authors created a high image quality. A good accuracy can be obtained for the measured SIF, and the crack tip can be mechanically sensed based on the same strain field. They found the use of the strain field, which in the displacement field removes difficulties associated with the rigid body motion of the analysis of the damaged structure. Some used the DIC technique in order to obtain the crack propagation of given material plates.[130] They used pure titanium as the material type, and the SIF was determined on T-stress and plastic zone size. Tasdemir[131] used a single edge-notch bend test to determine the mode I SIF of polycarbonate material. The author simultaneously recorded throughout the examinations the force, displacement, and images of the near crack tip region. The DIC method was used to obtain a full-field measurement of displacements and strains near the tip of the crack.

The determination of SIF for modes I and II using the DIC method has been done by Tavares et al.[126] They combined experimental and numerical studies to evaluate the SIF based on LEFM concepts. Roux-Langlois et al.[132] simulated the experimental case study based on Williams' series for fatigue crack growth identification. The authors evaluated strain by DIC identification and adopted the X-FEM method to simulate and validate the experimental data. They considered an EPFM simulation to validate the results. Harilal et al.[143] used an experimental approach in order to obtain the SIF of the cracked specimen. The authors considered two types of specimens: single edge notch (SEN) and center slant crack (CSC) made from the Al 2014-T6 alloy. They adopted the DIC method in order to obtain a strain field around the crack area.

Gonzales et al.[133] analytically and experimentally determined the SIF and the pseudo SIFs of the fatigue cracks in the presence of a crack closer, crack tip plasticity, and blunting using the DIC method. Manthiramoorthy et al.[134] determined mode I SIF using the DIC technique for a compact tension (CT) specimen of polycarbonate material. Mokhtarishirazabad et al.[135] presented a structural health monitoring (SHM) based DIC method, and the analytical solution was presented. The authors acquired a sample of aluminum alloy 2024-T3 CT specimen, which has an edge crack from the V-notch under cyclic loading for different load levels. In their study, the aim was to determine the SIF experimental value in a continuous mode throughout cyclic loads. Dai et al.[136] adopted DIC and acoustic emission (AE) methods in order to obtain SIF, crack tip position, crack extension length, and the length of the fracture process zone in the crack extension process. The test was conducted for concrete specimens and three-point bending conditions.

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4. CHALLENGES AND OPPORTUNITIES

Wu[70] reviewed and recognized the guidelines for the investigator who would like to use a PZT actuator in engineering applications such as repairing a damaged beam subjected to a static transverse load. Wang et al.[137] illustrated that future works may focus on the use of advanced and stronger PZT patches, such as stack PZT layers, for the enhancement and reconstruction of thicker structures that require larger forces. In addition, for different structures with multiple delaminations, the use of PZT fibers embedded in the damaged structure would be a more efficient way. Based on the existing work, it can be concluded that thinner PZT transfers higher forces concerning voltage to control host structures, and for sensing purposes lower electric fields are sufficient to sense the host structures. Abuzaid et al.[15] reviewed the guidelines for the investigators who were interested in using the PZT patches in engineering applications. Also, a review has been found in which the authors aimed to review the piezoelectric material and its mechanical and electrical effects considering the fundamentals of fracture mechanics under thermos-mechanical loading.[138]

In general, the crack behavior of materials was reviewed by Amin et al.,[139] and a comparative study has been performed to show and express the numerous types of cracks which occur in material structures. This will give an idea about the crack damage propagation in numerous ways, and this could repair or evaluate the crack using the PZT actuators. The author's work intends to determine and identify the governing equation of piezoelectric effects on different application purposes which have been shown in Figure 4. Considering all these applications (Figure 4), structural health monitoring (SHM) was the major consideration for the aerospace industry, and it has been well-reviewed by Qing et al.[140] and highlighted the significant importance of the piezoelectric transducer. However, SHM is a huge field[10,11] as a part of smart material application, but this review is only focused on the active repair of damaged structures, particularly bonded piezoelectric actuators in a crack thin plate.

From the present investigations, it has been observed that low mechanical loads could spoil a structure and create a small crack at the internal coat, which may spread and be the reason for failure. These types of spoiled structures will lead to a significant reduction in the mechanical properties of the materials. Therefore, in order to repair such damaged isotropic and orthotropic material types of structures, smart materials like PZT patches have been used, and they were found to be effective in increasing the service life and reducing maintenance costs. After an in-depth and exhaustive review of the previous work on active repair, it was found that the solutions were based on three methods: analytical, numerical/FEM, and experimental. Almost 90% of the previous studies used mode I compared to mode II and mode III (mixed-mode) because the opening mode (mode I) is the most effective phenomenon in damaged structures. Also, the maximum work has been done on edge-cracked plates using experimental, FE, and analytical methods compared to the center-cracked plate. One of the reasons for selecting the edge-cracked plate is the ease of preparation of the experimental model and the variation of geometrical factors being much less, for example, approximately the difference of 0.12 which was observed from Tada's formula.

It has been noted that patch size, thickness, piezo-material, and several applied patches are essential in the repair mechanism. It is also observed that the maximum work has been performed in delamination control of the beam, which is actively controlled by PZT actuators. The use of smart materials is now accepted with new advanced technology in such a way that the use of PZT materials is enormous for different engineering applications. PZT actuators in the field of repair mechanisms of damaged structures were considered by many scholars over the last two decades, and they investigated them with numerous results. The researchers performed mathematical modeling of the influence of PZT actuator repair for a damaged structure. From the literature, it is observed that there were many analytical methods to calculate stress intensity and stress concentration factors of cracked materials like energy release rates and virtual crack closer techniques. In Table 1, an attempt has been made to differentiate each methodology of this work considering some key points.

Table 1. Comparison of Active Repair Methods

Key Point	Analytical	Numerical	Experimental
Method	Mathematically solved	Software required	Difficult to process
Cost	Low	Medium	High
Accuracy in results	Required number of trails	Required mesh independence study	High
Fracture mechanics	Theoretical background	ANSYS APDL background	ASTM standard
Piezoelectric actuator	Difficult to relate	Material element type	Sensitive study/ setup
In aerospace applications	Few studies reported	Number of studies reported	Prototype studies

The use of PZT actuators offered a better result with an increase in the service life of damaged structures through active repair mechanics by their electromechanical characterization. It is also identified in this review that the PZT actuator location is significant to determining the SIF because the application of piezoelectric actuators is still challenging since a considerably high driving voltage is needed to attain practical forces or displacements, and thus the real-world application of the actuators is still limited.[106] However, the location of the PZT actuator was used in the cracked plate placed above and below the crack area in order to produce a compression load with the applied voltage of the PZT electrodes. Moreover, laminated composite plates are also considered because the delamination control uses a PZT actuator and is simplified by numerical, analytical, and experimental solutions.

All previous researchers specified that PZT materials mainly concentrated on the global behavior of structures. The investigation of the actuation of the PZT actuator and its significant effect on the limited fracture toughness and fatigue limit of the isotropic and orthotropic structures needs to be explored more through a strong concept of research methods, excluding the stress reduction near the delaminated zone because this concept has been studied well in the literature. The use of smart materials like the PZT actuator will bring a change in the improvement of mechanical properties after the repair of the damaged structure due to its electromechanical effects. From the literature, it was found that the PZT actuator was possibly used to increase the structure's life, provide

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Table 2. Different Methodologies Used for Cracked Plate and Delamination Control

Type of Material	Technique Adopted	Number/Types of PZT Patches	Focused Parameters	Limitations	Reference
Steel, aluminum 2014-T6 alloy, 2024-T351 alloy, AA6082-T6 alloy, titanium, polycarbonate (MAKROLON), and isotropic material type	DIC technique	No patch	Determination of SIF	Fracture mechanics	126, 127, 130, 131, 143
32 layers of carbon fiber reinforced epoxy plate	Strain ERR for stress ratio effect	No patch	Mixed-mode fatigue delamination growth/damage mechanisms/crack growth rate	Delamination effect without repair	71
Nonhomogeneous material/orthotropic material plate	Element-free Galerkin (EFG) method/maximum tangential principal stress (MTPS)	No patch	ERR (ERR)/mixed-mode stress intensity factor (SIF)/crack propagation kink angles	Use of PZT patches will be attractive for this solution	144
Cracked functionally graded material (FGM) columns	Analytical solution using governing equation/fracture mechanics	2 (above and below)	Stability analysis/effect of buckling load	Best location of the patch is on the skin surface which reduces the crack opening	145, 146
Rectangular material plate	Stiffness ratio/strain induce	2 (top/bottom) 2 (left/right)around a circular hole	Reduction of stress concentration factor	SIF is also effective to simplify	147
Cantilever beam	Finite element method	1 (bottom of novel cut)	Deflection of a cracked beam repaired with a PZT patch	FEM analysis allows a detailed understanding of active repairs	63
Simply supported and cantilever beam	Multidomain boundary integral formulation and spring model	2 (single and multi-layered)	Displacements, electric potential, and friction coefficient	Friction contact does not affect the repairing mechanism	40, 41
Cantilever beam and drop ply composite	Multidomain boundary integral formulation and spring model	2 (single and multi-layered)	Total ERR distribution, tangential and normal crack surface relative displacements	The best location for the patch is on the skin surface which reduces the crack opening	148
Timber specimen	Real-time monitoring	PZT and copper sheet	Time domain signal during the experimental test	Can change the material type of thin plates	149
Square plate	FEM analysis using ANSYS	2 (above and below)	Applied voltage, delamination location, shear stress	Huge voltages applied to electrodes eliminate delamination	74

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stiffness against structure buckling, and decrease the stress or strain concentration at a cracked part.

From the studies, we also observed that the structures have many types like a plate, shell, beam, column, pipe, etc., but in this study, most of the considered cases are based on a plate, beam, and delamination control. Most of the work has been done for thin-plate structures under in-plane stress conditions. Next, the beam is considered necessary for two ways of repair such as delamination control for the laminate beam and repair of the damaged isotropic beam. In the year 2017, a few studies were found on the active repair of metallic structures. For instance, Abuzaid et al.[97,116,117,141] used PZT patches for the repair of the plate through an experimental, numerical, and analytical method since it can be developed for metallic and nonmetallic materials of repair. However, in the next level of study, it can be possible to consider tubes/pipes or other types of structures for active repair because this type of structural repair has been found in passive repair.[142] Furthermore, a few cases were also found for the experimental study on the repair of a beam. Therefore, another type of damaged structure can also be possible for experimental investigation.

To get more ideas on experimental work focused on the digital image correlation (DIC) technique, which was used for the determination of SIF for a damaged structure, most of the studies have been found for cyclic loading effects with an LEFM and a few for EPFM assumptions. From the existing experimental work and DIC technique for the determination of fracture parameters such as SIF, it has been a slight sign for the researchers to use this technique for repaired structures or bonded thin plates with piezoelectric actuators. Moreover, this could make it easier to investigate SIF compared to using a strain gauge method. Table 2 shows the previous work performed by the researchers for the repair of plate/delamination control with PZT actuator patches and some without PZT patches to highlight the contribution and limitations.

5. CONCLUSION

In order to investigate the stress intensity and concentration factor for a damaged or cracked structure, analytical, numerical, and experimental methods were critically overviewed, and the following conclusions and recommendations have been made.

- Maximum reduction in the stress intensity factor was found at approximately 36%−39% after repairing the damaged thin plate under plane stress conditions in mode I loading effects using bonded piezoelectric actuators in a thin plate based on the current literature study.
- Adhesively bonded joints are adequate to transmit stresses and are essential in the manufacturing of engineering structures, and the current investigation shows the reduction of stress intensity and concentration factor in a thin plate.
- Provided a brief idea about active repair methods using bonded piezoelectric actuators in a cracked plate through the analytical/mathematical modeling, finite element method/numerical, and experimental techniques.
    - Mathematical modeling was performed from the linear elastic fracture mechanics with a few theoretical approaches such as crack closer and weight function method.
    - The finite element method for active repair has been done through the ANSYS and Abaqus tools; however, some of the unrepaired work was done from the Franc2D commercial tool.
    - As per the simulation and analytical work, only a few studies have been found in which piezoelectric actuators were used to reduce the SIF, but to express more studies the DIC technique has been explored which shows the importance of piezoelectric actuators.
- In this appraisal, strategies are recognized for those researchers who are interested in using piezoelectric actuators for the applications of the engineering structure such as plates, tubes, pipes, etc. These strategies are types of piezoelectric materials and repair methods. The major challenge was resolved: the PZT actuator is resilient yet exceedingly brittle, making it more susceptible to inadvertent fracture. Also, it is crucial to take into account the layer created by the link between the host structures and the piezoelectric actuators when structures are bonded together via piezoelectric patching.
- The future recommendations include investigating the gaps in previous studies through transport ideas and suggestions. In particular recommendations, the piezoelectric actuator can be used to reduce the SIF in different mode conditions of crack damage propagation such as mode II, mode III, and mixed mode. Additionally, it can determine the J integral with PZT effects which are lacking in the literature.
- In summary, these strategies can help and serve as the means for investigators, predominantly within the initial stage of this field, to develop new innovative concepts.

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Notes

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SYMBOLS

a	Crack Length
K_I	Stress Intensity Factor
$K_{I(piezo)}$	Stress Intensity Factor due to a Piezoelectric Actuator
$K_{I(total)}$	Total Stress Intensity Factor
σ or σ_0	Applied Tensile Load/Stress
σ_{pz} or σ_{piezo}	Piezoelectric Actuator Load
V	Applied Piezoelectric Voltage
E	Cracked Plate Young's Modulus
ν	Cracked Plate Poison's ratio
G	Cracked Plate Shear Modulus
S_1	Mechanical strain
D_3	Electric Displacement
E_3	Electric Field
d_{31}	Piezoelectric Coefficient
S	Stiffness Ratio
Λ	Piezoelectric Strain
T	Distributed Electrode Width
ε_{33}^{T}	Dielectric Constant at Zero Stress
s_{11}^{E}	Mechanical Compliance at Zero Electric Field
S_{piezo}	Piezoelectric Actuator Force
u_y	Crack Displacement at the y-Direction
Γ	Crack Perimeter

ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AI	Aluminum
ASTM	American Society for Testing and Materials
CFRP	Carbon Fiber Reinforced Plastic
CSC	Centre Slant Crack
Coef	Coefficient
DIC	Digital Image Correlation
ERR	Energy Release Rate
EPFM	Elastic–Plastic Fracture Mechanics
FE	Finite Element
FGM	Functionally Graded Material
LEFM	Linear Elastic Factor Mechanics
LMN	Lead Meta Niobate
LT	Lead Titanate
MEMS	Micro-Electromechanical Systems
MIS	Mesh Independence Study
NSIF	Normalized Stress Intensity Factor
SEN	Single Edge Notch
SHM	Structural Health Monitoring
SIF or K	Stress Intensity Factor
SPN	Sodium Potassium Niobate
PZT	Piezoelectric Actuator/Lead Zirconate Titanate
PMN	Lead Magnesium Niobate
PERR	Potential Energy Release Rate
UCCI	Universal Crack Closure Integral

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