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Review

Survey of Active Structural Control and Repair Using Piezoelectric Patches

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Abstract: The piezoelectric actuator has gained popularity over the last few years. Attention has been directed towards the study of their electromechanical response in active repair and the control of damaged structures. This has been made possible through the development of various numerical and analytical techniques for such studies. The shift of focus towards the piezoelectric based approaches has been due to their advantages, which include strategic cost benefits in maintenance, as well as an increase in the life cycle of the repaired structures. Furthermore, adhesively bonded joints are widely used in the manufacturing and repairing of structures in many industries, especially automotive and aerospace engineering. This is due to the requirement for lightweight materials as well as the potential adhesive used to join materials with different characteristics. The piezoelectric actuator has also shown the capacity in controlling and lowering the shear stress concentration and joint edge peel in adhesively bonded joint systems. The structure's control of stress and repair can generally be viewed as a reinforcement that influences the structure's damage tolerance. Therefore, the interest of this review is on the applications of the piezoelectric actuators in both structural damage and the bonded adhesive joint system. The specific goal is to recognize the contemporary scientific challenges, including future opportunities.

Keywords: piezoelectric actuator; active repair; bonded adhesive joint system

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1. Introduction

Damage in structures often occurs due to factors such as corrosion, fatigue, and accidents. Such damage, when left unattended, can grow at an alarming rate, due to the singularity of the stress and strain in the vicinity of the damage. This may bring about several effects, which include higher vibration levels, decreases in the amount of load that can be carried, component performance degradation, and the high possibility of failure. Most of the time, repairing, rather than immediately replacing the damaged components, would significantly prolong their service life. Active damage control and repair can extend service life and at the same time be a cost efficient alternative compared to immediately replacing damaged components.

Lately, a lot of attention has been directed towards the applications of smart materials in engineering structures. These materials possess some attributes, which can be altered desirably under a controlled environment through temperature, stress, and an electric or a magnetic field, which act as external stimuli. The most typical examples of such materials that are widely employed in different areas are the shape memory alloys and piezoelectric materials. The latter of the two are characterized by a trait referred to as the electromechanical effect. This trait is due to the effect of interaction between electrical and mechanical properties of a given material.

When a mechanical stress is applied to a piezoelectric material, an electric field is produced (direct piezoelectric effect), and, conversely, mechanical deformation will be generated when an electric field is applied (converse piezoelectric effect). Due to their electric–mechanical coupling effects, piezoelectric materials are widely used as sensors or actuators in many engineering structures. In addition, the piezoelectric actuator's response to a change of the electric field or to the deformation structure is extremely fast, which allows for repair and control to be adjusted instantly when the external load is altered.

In general, repair can be broadly classified into passive and active repair. Over the last two decades, only passive patch repair work has been studied, and currently researchers are working on active repair studies involving smart materials [1,2].

Active damage control and repair is a prominent technique used for restoring the structural integrity of damaged parts. This active damage control and repair technique, obtained by means of piezoelectric actuators, is based on the converse piezoelectric effect, according to which the local moment/force induced by an applied electric field across the piezoelectric actuators can help the structure to oppose known high stress/strain concentration, caused by the external load and, consequently, reduce the severity of any damage.

None of the existing research related to applications of piezoelectric actuators in repair and control have presented a clear definition of the terms "Active Repair" [3,4] or "Control" [5,6]. The terms have been used interchangeably by several researchers in describing the same concept. In this work, the term "control" is proposed to portray the "action of mitigating or delaying the effects of damage propagation", while for the term "repair", the portrayed meaning is "the action of erasing or removing the damage from a structure". In other words, repair means the erasing of damage so that structural integrity is restored, and the structure behaves like a healthy or undamaged structure.

In this review, an application of the piezoelectric actuator to repair and control the stress distribution, both on damaged structures and adhesive bonded joint systems, will be considered. The piezoelectric constitutive equation will be presented in the next section, followed by a look at the different applications of the piezoelectric actuators. The next two sections will present application of the piezoelectric actuator in the active repair and control of isotropic and composite material respectively. Once that is done, the following section will show the use of piezoelectric actuators in the control of stresses in the adhesive joints, and the effectiveness of the bonding on the performance of the piezoelectric actuators. Finally, the last section will give observations and further research opportunities in this field.

2. Piezoelectric Materials

Piezoelectric materials have been used in a wide variety of smart devices and structural applications, owing to their capabilities of actuating and sensing, their easiness to control, their light weight, and their low cost. Due to the different applications of the piezoelectric materials in engineering structures, many different forms of piezoelectric materials are manufactured, such as fibres, patches, plates, cylinders and thin-film stacks. Some popular uses of actuation materials are lead zirconate titanate (PZT) and the Macro Fibre Composite (MFC) [7,8]. The MFC actuator is constructed using piezofibers surrounded in an epoxy matrix and covered with a Kapton shell [9]. The construction of this actuator allows it to be extremely flexible, as well as resistant to damage and environmental conditions. Additionally, the MFC uses an interdigitated electrode pattern that capitalizes on the higher d33 piezoelectric coupling coefficient, which means the device is more efficient in converting energy between the mechanical and electrical domains. The piezoceramic PZT material is effective but extremely brittle, and susceptible to accidental breakage, making it the less robust than the MFC [10–12].

2.1. The Piezoelectric Effect

Piezoelectric materials have attracted significant attention for application as actuators for controlling and as sensors for monitoring the response of structures. This is because of their ability to couple electrical and mechanical energy. Piezoelectricity represents an electromechanical phenomenon that involves interaction, without central symmetry, between the electrical and the mechanical behaviour of a material. A typical piezoelectric material produces an electric field in response to an external load (direct piezoelectric effect), and conversely, mechanical deformation will be generated when an electric field is applied (converse piezoelectric effect) [13–15]. In the application of piezoelectric materials, the direct effect is normally used for sensory technology, while the converse effect is used for actuating technology [16].

2.2. Piezoelectric Constitutive Equations

Under the influence of voltage and stresses, the magnitude of resulting strain and the level of charge accumulated by the piezoelectric material dictate the sensing and actuation characteristics of such material. All the constituent relations under a piezoelectric material can be used to compute these properties. Macroscopically, piezoelectric materials exhibit a field–strain relation [14]. The relation is nearly linear for low electric field, which may provide many advantages when employing piezoelectric materials in system modelling and control realization. However, the polarization saturates at high electric field, and domains expand and switch. This causes significant nonlinear behaviour that can be detrimental when employing piezoelectric materials in control implementation associated with high electric field [16,17]. In many applications of piezoelectric materials to continuous structures, the linear constitutive model is adopted despite the nonlinear hysteresis behaviour at a high electric field.

The direct and converse piezoelectric phenomena, involving an interaction between the mechanical behaviours of a material, can be usefully modelled by linear constitutive equations involving two mechanical variables, and two electrical variables. In matrix form, the equations governing the direct piezoelectric effect, and the converse piezoelectric effect are written respectively as [18]:

$$\{\mathrm{D}\} = [\mathrm{e}]^{\mathrm{T}}\{\mathrm{S}\} + [\varepsilon^{\mathrm{S}}]\{\mathrm{E}\} \tag{1}$$

$$\{\mathrm{T}\} = [\mathrm{c}^{\mathrm{E}}]\{\mathrm{S}\} - [\mathrm{e}]\{\mathrm{E}\} \tag{2}$$

Where $\{\mathrm{D}\}$ is the electric displacement vector, $[\mathrm{e}]^{\mathrm{T}}$ is the transpose of the dielectric permittivity matrix $[\mathrm{e}]$, $\{\mathrm{S}\}$ is the strain vector, $[\varepsilon^{\mathrm{S}}]$ is the dielectric matrix at constant mechanical strain, $\{\mathrm{E}\}$ is the electric field vector, $\{\mathrm{T}\}$ is the stress vector and $[\mathrm{c}^{\mathrm{E}}]$ is the matrix of elastic coefficients at constant electric field strength. The same relationship can be written in three other forms, depending on which variables are chosen to be independent [18]. The direct relationship given by Equation (1) is normally used when modelling the sensing capability of the piezoelectric material, whereas the actuator capability is modelled using the converse relationship given by Equation (2).

2.3. Piezoelectric Sensors and Actuators Applications in Engineering Structures

Several attractive and significant traits can be found within the piezoelectric based actuators and sensors. Such traits include: consistency or conformability, light weight, high tolerance, and high resistance to harsh environments. Normally, the structure that has been patched through by the piezoelectric material receives a share of the strain, which is a product of the voltage applied to the material. The resulting effect in turn can be a reshape of the structure, as well as a motion outcome, and this characteristic reaction of the piezoelectric patch is referred to as "actuation". The desirable structural response's characteristics can be achieved through a variation of the voltage directed towards the piezoelectric actuator. On the other hand, when a piezoelectric material is subjected to mechanical strain, then the resulting outcome is the voltage being produced by the material, and hence the material becomes a good candidate to be employed as a motion sensor.

Piezoelectric materials have been used in a wide array of applications in engineering structures, aerospace, industrial and medical fields, with distinctly different characteristics. The main application of the piezoelectric material in engineering structures can be classified into different categories, as shown in Figure 1. The classification is based on previous research that has been done in this field. This will be helpful to researchers, particularly in the precocious stages of investigation, to get a global idea about the research areas of piezoelectric material. There are different review papers in the various applications of the piezoelectric actuator in the literature, which are referenced here for the reader [10,19–24].

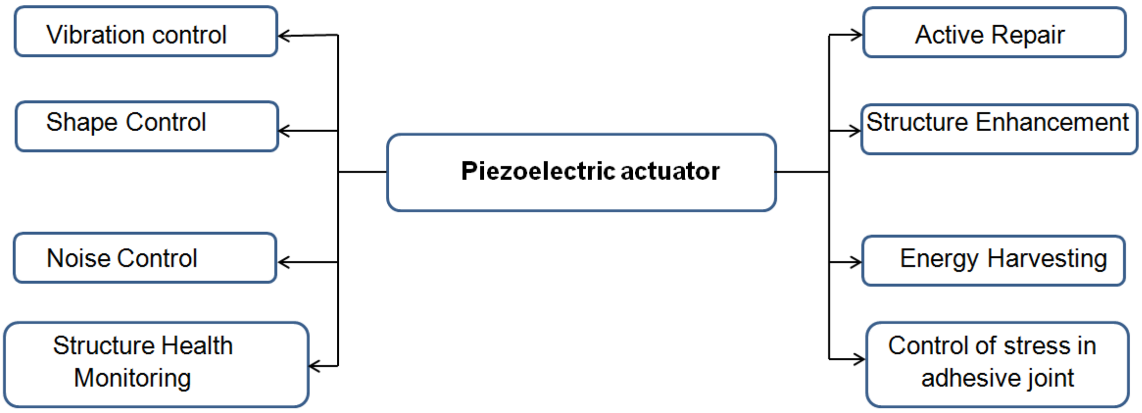


Figure 1. Classification of main piezoelectric material application.

Figure 2 presents the statistics and timeline related to different areas of application in the context of piezoelectric materials. The figure specifically reflects upon the materials' usage within engineering structures.

The expectation is that this number will continue rising in the future. This expectation is based on the obvious fact that these materials have already gained a reputation, and due to their advanced and progressive nature, they have opened up doors for new possibilities in solving various engineering problems which were previously stumbling blocks for conventional methods. The existing literature in the applied areas of the structural health monitoring and shape and vibration controls provide a clear picture of the progressive growth of the piezoelectric actuators within such fields. As pointed out by the given data, energy harvesting is one of the application areas where these actuators have been increasingly employed, which is evident from the amount of research conducted on the respective actuators. On the other hand, the study of active repair is still within its infancy. One important thing to note is that some of the properties, like flexibility and high impact resistance, make the piezoelectric based MFC actuator a preferred choice, in comparison to ceramic based materials.

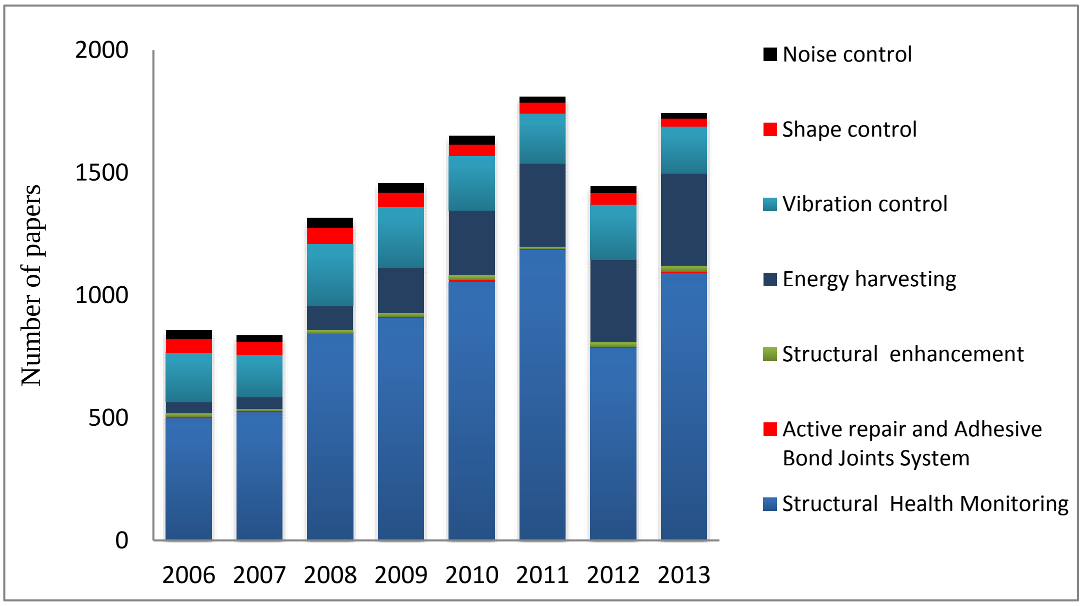


Figure 2. Research trend.

3. Active Structural Repair Using Piezoelectric Materials

One of the most researched and investigated areas is the repairing of damaged structures. Most of these studies have been on restoring such structures to their usual or expected functioning conditions, in order to prevent them from failing. The main goal that one seeks to achieve during the repair design process is to have a good reinforcement of the structure, so that the damaged part is subjected to lower stress or strain concentration. The evolution of smart engineering structures and materials has enabled significant development, with desirable research outcomes that has resulted in an increased usage of piezoelectric materials in structural repairs. The local force/moment induced by the piezoelectric layer has mainly been employed as the research-based method of approach in order to reduce the stress's singularity, which is achieved through preventing the loss of bending stiffness, caused by the discontinuity at the damaged area. This review presents an overview of the recent advances and developments in the study of active repair. Various methods that include fracture mechanics, mechanics of materials, boundary elements, and repair criteria, based on the restoration of the beam's natural frequencies, have been created as strategies and methodologies to facilitate the study of active repair.

3.1. Active Repair of Isotropic Materials

The use of piezoelectric materials as integrated parts has been found to affect the properties of the host structure. In the paper reviewed by Rogers [25], researchers at Virginia Tech Research Centre demonstrated experimentally that piezoelectric actuators can actively reduce the mechanical strain concentrations from transverse cracks near holes and notches, and other locations of known high stress concentration. Shah *et al.* [26] investigated the effect of piezoelectric patches around a hole in an isotropic plate. The objective of the research was to reduce stress concentration in the vicinity of a hole. Finite-element analysis was performed on a finite plate with a central circular hole under a far-field applied tensile load, with the piezoelectric patch placement in the tensile and compressive regions around the hole. It was pointed out that application of an electric field to produce a plane expansion of the piezoelectric patch would alter the compressive zone in such a way that it resulted in reduction of stress concentration in the tensile zone. The results demonstrated that, for the given geometry, a one-third reduction in the concentration of the stress around a hole can be achieved by active piezoelectric patches.

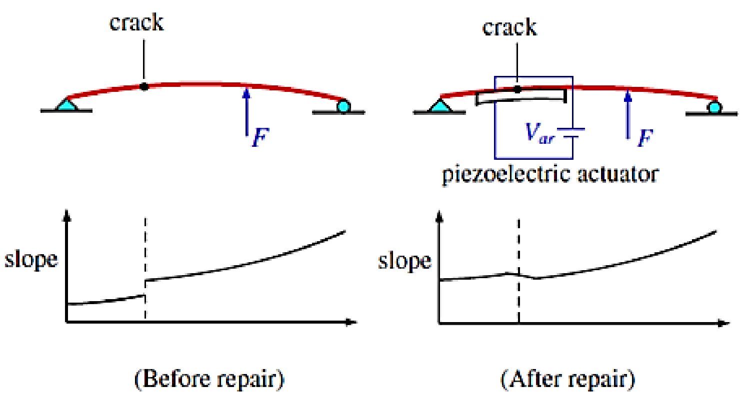


Figure 3. Slope continuity criterion for active repair [27].

Wang *et al.* [27] have studied the repair of a cracked beam under a static transverse loading. To assess the effect of the active repair, the piezoelectric patch was employed as an actuator to generate a counteracting bending moment to reduce the stress concentration at the crack tip. They employed a "mechanics of materials" approach through Euler–Bernoulli beam theory to calculate required actuation voltage to decrease the concentration of stress on the crack area of the beam. The research result indicated that, the variation of the slope of continuity at the crack position for a simple support beam, when subjected to a bending moment, can be removed by applying an appropriate voltage to the piezoelectric layer. Figure 3 shows a slope continuity criterion for active repair.

In their research work, Wang and Quek [4] investigated the method of repairing beam structures containing cracks. The authors looked into the structures that were under compressive loading, and managed to repair the cracks, thanks to the utilization of the piezoelectric material. This was achieved based on a model of the rotational discontinuity at the crack location that depicted the design of the actuation voltage. The repair of the cracked column was then conducted based on the model and through various boundary conditions. With the actuation of the piezoelectric patch, the resulting induced local bending moment caused an efficient compensation for the decreased buckling capacity. Compared to the passive repair models, the authors' model proved to be more advantageous, as it enabled various voltages to be used for the crack repair at different intensities and depths, as well as at different locations.

However, the exact strategy cannot always be applied for the case of the same beam under a dynamic load. A closed-loop feedback control repair method, using a piezoelectric patch for repair of a notched beam subjected to a dynamic loading, was proposed by Wang *et al.* [28]. The piezoelectric patch was used as both a vibration sensor and a repair actuator in the closed-loop feedback control process. Their methodology was based on the restoration of resonant frequency back to the frequency of a healthy/undamaged beam by reducing the strain concentration under dynamic loading through the application of an appropriate actuation voltage to the piezoelectric actuators bonded around the notch. Their results revealed that the resonant frequency of the cracked beam after repair would be recovered by 97% with the use of the piezoelectric patch as shown in Figure 4 below. In their work, only the global behavior of the cracked beam was analysed, and the local effects of the crack were not verified.

In the study conducted by Sekine [29], the cracks formed from aircraft panels were explored for repair. In the author's study, the cracks were repaired with piezoelectric patches, and the efficiency of the patching was investigated. The resulting improvement of efficiency in patching based on the use of the piezoelectric actuators was also given by the author.

Another line of investigation can be found in the study conducted by Providakis [3], who explored structures under dynamic loading. In his work, the author presented an investigation related to the repair of the cracks formed in the structures, based on the electromechanical admittance (EMA) approach. It was shown that the crack's closure was achieved through application of a suitable electric field on the outer surface of the piezoelectric (PZT) patches. With this approach, the electromechanical admittance signature, extracted at the respective PZT patch's electrical terminals, is altered as a result. This resulting effect causes a shift in the structure's state to a healthy one, and the patch was considered as an Admittance Calculating Sensor (ACS). The change of state, or altering of the EMA, was what dictated the repair process and where the criterion employed in the process originates from. The process produces forces which restore the state of the structure and that counteract the effects caused by the external dynamic load to the cracked structure. These forces depend on the computed electric voltages, based on the proposed methodology by the author.

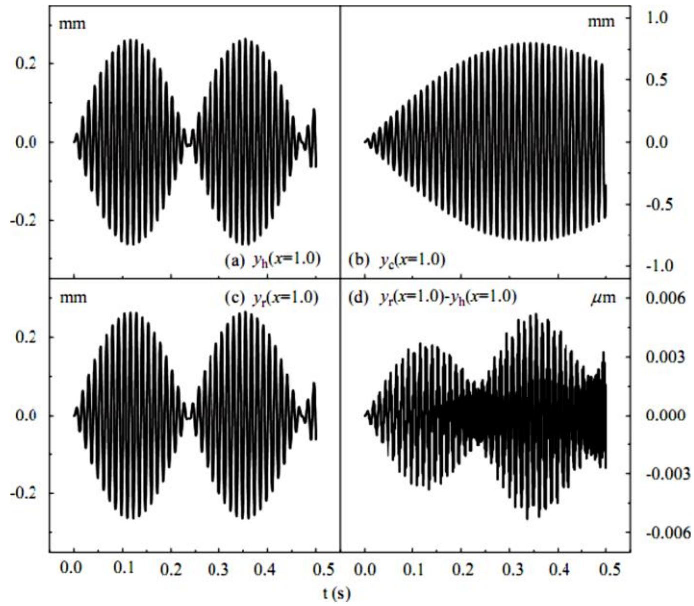


Figure 4. Time history of tip displacement predicted by proposed model for (**a**) healthy beam, (**b**) cracked beam, (**c**) repaired beam, and (**d**) difference between repaired and healthy beam [28].

Liu's [30,31] work presented a repair process based on the measure of Linear Elastic Fracture Mechanics (LEFM). His analysis targeted an estimation of the repair performance where the approach was based on the adaptation of the strain energy density theory, and contact analyses within the plane strain's finite element analysis. The criterion that Liu employed is not the same as the one used in [31], and it is presented in Figure 5 below. Liu's repair mechanism, along with the criterion, employs the piezoelectric actuator. In this case, as the crack tip's strain energy density factor was reduced to the minimum value, the resulting effect was then the repaired crack. On the other hand, the piezoelectric actuator used in [31], which was based on the plane strain finite element analysis, was incapable of a full closure of the edge crack. Another noted observation was that the crack surfaces start contacting each other as the reduction in the strain energy density factor reaches the minimum value. Moreover, his work highlighted a significant result: that the crack contact has to be considered when dealing with the repair in context. The important point was that incorrect results would be obtained when the crack contact was ignored, causing the occurrence of penetration between both surfaces of the crack. In turn, it was advised against the usage of higher voltage than the desired one. The preference of the usage of the desired voltage is because a higher voltage causes intensification of stress concentration near the tip of the crack. It is then very significant in the structural repair to have an actual model for the purpose of deriving suitable actuation voltage. In addition to that, having a high length for the patch in active repair is not advantageous.

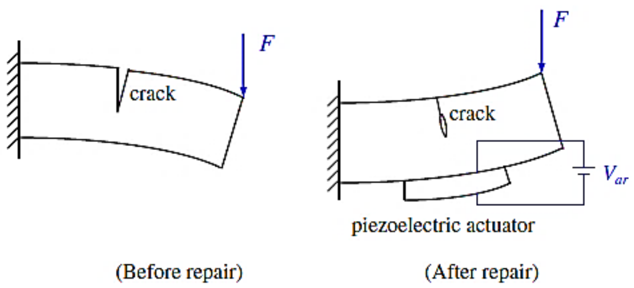


Figure 5. Fracture mechanics criterion for active repair [30].

Liu [30] used two criteria: a fracture mechanics criterion and a slope of continuity criterion, to assess the effects of piezoelectric actuators on active repair through the plane strain finite element method. The results showed that a fracture mechanics criterion is better for defining the repair voltage.

In the work carried out by Ariaei *et al.* [32], cracked beams subjected to a moving mass with piezoelectric materials were studied. An analytical method for the active repair of the cracked beams was then developed. The authors employed the "Timoshenko Beam Theory" to obtain the beam's equations of motion, while taking into consideration the dynamic effect of a moving mass. Another criterion used by the authors for repair was based on adjusting the resonant frequency of the cracked beam. The frequency was adjusted to match the one of a healthy beam, as well for a desired voltage of actuation to be reached.

Another method of repair is based on the boundary element method developed by Alaimo *et al.* [33,34]. In this approach, the damaged structure considered was isotropic, and characterized by the behaviour of dynamic fracture mechanics. A Mode I dynamic Stress Intensity Factor (SIF) was given, which entails a description on the repair mechanisms employed for the damaged structure. The damaged structure was considered for different dynamic repair voltages. The authors presented the effect of the piezoelectric patch through its adhesive actuation capability. It was also noted that the interface bonding between the piezoelectric patch and the host structure cannot be neglected, as any loss in the transfer of shear stress would influence the performance of repair.

The study conducted by Platz *et al.* [35,36] examined thin, homogeneous aluminium panels, for the lowering of damage propagation. In their work, the authors explored the effect of piezoelectric patches on the respective panels, through numerical as well as experimental approaches. Their approach was based on the idea that mechanical compression forces are induced within the panel's cracked area, specifically near the tip of the crack. This was done so that the extension, or propagation, of the crack was lessened, if not avoided. The following three cases for an aluminium-based cracked structure were examined by the authors in different actuator types: (i) The host structure without piezoelectric, (ii) with passive piezoelectric, and (iii) with activated piezoelectric patches (see Figure 6). Through statistical analysis, and with comparison between active and passive actuators, the authors found better results for the active actuators. Their results showed that, with the mounting of an active piezoelectric actuator patch near the tip of the crack, a significant decrease in the crack propagation is obtained. The experiments were carried out under similar conditions for both types of actuators, and the significant lowering rate for the active patch was found to be about 20%.

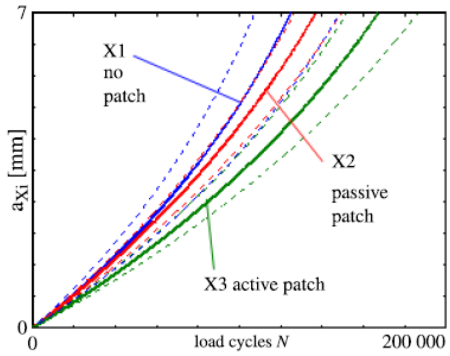


Figure 6. Summarized mean (——) and mean deviation (– – –) curves of crack length propagation a_{Xi} *versus* load cycles N according to no applied patch for case X1 (top), applied passive patch for case X2 (middle) and applied active patch for case X3 (bottom). [35].

An experiment, and a simulation using FEM, was conducted by Nan Wu *et al.* [37] to investigate the effectiveness of repair of a notched cantilever beam structure that was subjected to dynamic loading by use of piezoelectric patches. In the experiment, a small piezoelectric patch, used as a sensor, was placed on the notch position, to monitor the severity of the stress concentration around the notch area by measuring the charge output on the sensor, and a patch used as an actuator is located around the notch area to generate a required bending moment, by employing an actuation voltage to reduce the stress concentration at the notch position.

The bending moment induced at the two ends of the piezoelectric actuator when the actuation voltage V_a is applied found from

$$M_e = R\int_{L}^{L+L_1}\frac{d^2w}{dx^2}, R = -gd_{31}\,e_{31}\,\frac{EHb_a\,(H^2-h^2)}{4\,c_v\,h\,(\psi+\alpha)}\} \tag{3}$$

where R is defined as the repair coefficient, E is the Young's modulus of the host beam, b_a, h are the width of and thickness of the piezoelectric actuator. ψ is given as $\mathrm{EH}/\mathrm{E}_p\mathrm{h}$. E_p is the equivalent Young's modulus of the piezoelectric patches, d_{31} is the piezoelectric charge coefficient and $\alpha = 6$ when a bending bar is considered. This moment with an opposite sign to the external load was applied to erase the stress singularity at the tips of the notch.

The results of the FEM simulation showed that the stress concentration at the crack tip was reduced by 95.8% when the piezoelectric patch was subjected to an appropriate actuation voltage, based on the calculation of the feedback factor from the model, as seen in Figure 7.

Yan *et al.* [38] studied the Stress Intensity Factor (SIF) of the cracked panel repaired with a multi-layered piezoelectric patch using the finite element method. The effect of the parameters on the SIF, including the piezoelectric patch layer and the geometric size of the patch, was numerically investigated. The outline of the result showed that better repair efficiency was obtained with the increase of voltage; it was also found to be beneficial to use more layers in the piezoelectric patch as the thickness of the patch is fixed.

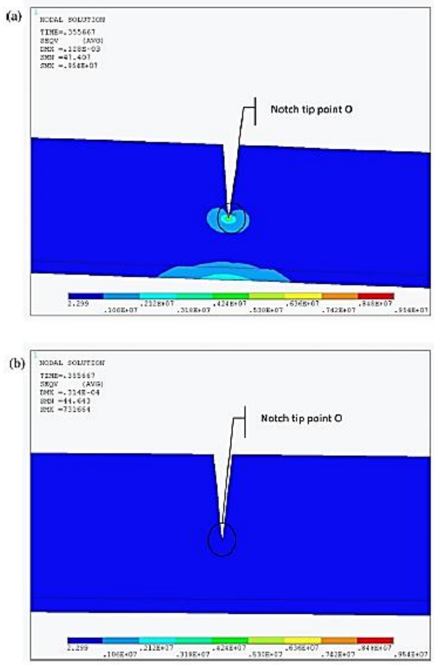


Figure 7. The Von Mises stress distribution at the notch position of the vibrating cantilever beam at (**a**) gain factor = 0 and (**b**) gain factor = 74 [37].

3.2. Active Repair of Composite Structures

Composite structures have been increasingly used in load bearing structures because of their excellent strength-to-weight and stiffness-to-weight characteristics, compared to many conventional materials and metallic alloys [39]. Although metallic alloys can be made to have improved strength and stiffness, in contrast to composite materials, they do not offer substantial weight reductions [40]. Weight reduction does not only improve the performance, but also reduces the operational and maintenance cost of the aircraft. Despite having lots of advantages, composite structures in some cases show different limitations that are caused by stress concentrations between layers. Discontinuous change of material properties is the reason for occurrence of interlaminar stresses that often cause delamination failure [41]. Delamination may originate from manufacturing imperfections, cracks produced by fatigue or low velocity impact, stress concentration near geometrical/material discontinuity (such as joints and free edges), or due to high interlaminar stresses [42]. All of these imperfections gradually reduce the stability of the mechanical properties of composites, and require comprehensive study with experiments, as well as gaining numerical estimation under loading [43–45]. The failure modes of laminated structures when they fail under loads exceeding their load bearing capacity have been observed to be significantly different from that of isotropic materials [46].

Another line of investigation regarding the application of the piezoelectric actuators is based on numerical and experimental methods. These methods have been carried out on the specific area of the material application, known as active repair technology. Reduction of the stress/strain concentration in a delaminated structure was the main goal of such investigations. The main reason for this approach is that the control and restraint of possible growth or damage propagation can be achieved.

The effects of piezoelectric actuation on composite laminates have been investigated using a DCB (Double Cantilever Beam) numerical model by Shah *et al.* [47]. The stress distribution at the laminate's interface was observed to be affected by the applied voltage to the actuators. An increase in stress formation at the laminate interface would propagate cracks, while reduction in stress would arrest crack growth. They observed that the out-of-plane stresses of a laminated structure with delamination would be regulated through appropriate actuation near the flawed region. The actuation was achieved by means of embedding piezoelectric actuators near the flawed region. They demonstrated that the interlaminar stresses of the laminate can be reduced if the actuators were activated in a manner by which the strain produced by the actuation is against the Mode I load.

Another study considered a delaminated beam under the influence of intense static force. The consideration was done for the purpose of exploring the active repair of the beam through the use of piezoelectric patches. This study was carried out by Wang *et al.* [48] and a methodology was provided for the active repair. Piezoelectric patches were used in the active repair to counter the shear force's singularity at the delaminated tip. With the authors' approach, the patch was enabled in order to control the fracture's sliding or eliminate it altogether. On the other hand, the same type of beam structures, under the influence of compressive loading, was studied by Wang *et al.* [49] for the piezoelectric based repair. This work centered on various boundary conditions on the beams' bending in buckling mode. The beams' bending may have caused the fracture's sliding mode, in turn inducing a discontinuity of the shear stresses at the two tips of the delamination.

The study on the efficacy of repairing delaminated beams using the Finite Element Method (FEM) was done by Duan *et al.* [50]. The authors carried out the work with the intent of understanding the physical phenomena underlying the piezoelectric patch repair. In the results of their analysis (Figure 8), it was shown that the control and reduction in stress concentration can be achieved effectively through the use of relevant voltage on the piezoelectric actuator.

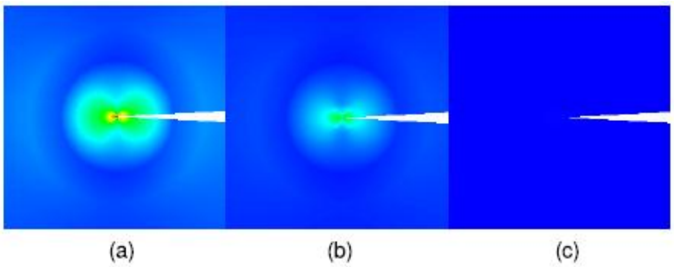
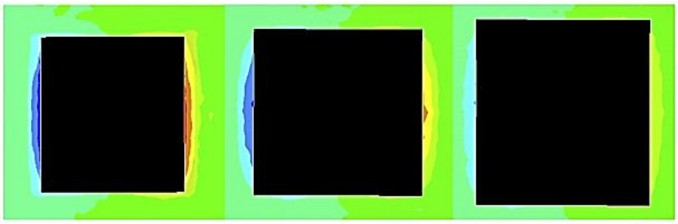


Figure 8. The Von Mises stress field around the crack tip with different applied voltages on piezoelectric patches: (**a**) 0 V, (**b**) 300 V and (**c**) 480 V [50].

Active repair for a vibrating beam containing delamination was investigated by Wu *et al.* [51]. In their research, they extended the scope of the research by Wang *et al.* [48] and developed a closed-loop feedback control repair methodology for the vibrating delaminated beam using piezoelectric patches for the optimal design of the voltage to be applied on the piezoelectric patch. Their methodology based on Euler–Bernoulli beam theory was found to be more applicable when the ratio of beam thickness to beam length is smaller.

An investigative work by Wu *et al.* [52] substantiated the degree to which the piezoelectric based repair techniques are significant when it comes to the patches' application in delaminated plates. The plates were explored both analytically and through an FEM model when they were subjected to a static transverse load. It was shown in the authors' results that when appropriate voltages are applied to the discrete electrodes (Figure 9), then the shear stress concentration is lowered as a result. The lowering of the shear concentration is wholly reflected upon its distribution along the plate's delamination edge. One noteworthy observation is that the authors' analytical model is restricted to static analysis. Therefore, it is of significant importance for the establishment of a precise piezoelectric-based model for the repair of delaminated plates subjected to dynamic loading.



(V=0v) (V=100v~150v) (V=165v~195v)

Figure 9. FEM simulation of shear stress distributions along delamination edges with different voltages (L1 = L2 = 0.1 m, a = b = 0.1 m, t = 0.005 m) [52].

Shaik Dawood *et al.* [6,53] have demonstrated the ability of piezoelectric actuators to reduce, or control, delamination in laminated composites subjected to low velocity impact loads. They used a cohesive based damage model to predict delamination, and their result showed that the piezoelectric actuation has an influence on the damage formation (delamination) in composite laminates. In a recent study, Shino *et al.* [5,54] were able to show, experimentally and numerically, that Mode I energy release of the DCB composite would be reduced by applying the electric field to a surface bonded actuator. Also, the effectiveness of the piezoelectric control depends on the actuator location, relative to the delamination. In their article, Shino *et al.* [54] suggested that the temperature dependence of the control performance has to be taken into account when designing cryogenic structures containing piezoelectric ceramics as actuators.

The work of Alaimo *et al.* [55,56] examined the underlying mechanisms for the active repair of delaminated composite structures through piezoelectric patches. They employed boundary Element analyses, for the purpose of the active repair process, and different methods of design were presented in their work. In their approach, two-dimensional boundary integral formulation was employed for the piezoelectric patches. They based their formulation on the technique of a multi-domain modelling process of the damaged composite host structures, along with the bonded piezoelectric patches. The finite stiffness of the bonding layers was taken into account through an implemented interface spring model that reflected the delamination surfaces' frictional contact. It has been shown in their analysis that the electromechanical response of piezoelectric devices is significantly influenced by the finite stiffness of the bonding layer. In addition, for the analysed delaminated structures, the repair mechanism is not influenced or affected by the frictional contact condition.

4. Stress Control of Adhesive Joints Using Piezoelectric Materials

Adhesively bonded joints are essential in the manufacturing and repair of spacecraft, aircraft, and automotive structures, due to their ability to join dissimilar materials. The loads between the adherents and adhesive are transferred in the form of shear and/or peel stresses through the adhesive layer. As a result, the failure of such adhesive joints commonly occurs prematurely, due to the presence of the stress concentration in the end regions of the adhesive interface bond lines. Therefore, it is desirable to reduce, or to control, the level of such stress concentration, which will lead to improving the joint's stiffness. Typical single-lap and single-strap joints are shown in Figure 10a.

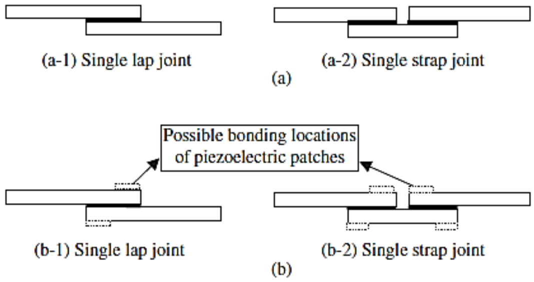


Figure 10. (**a**) Commonly used adhesive bonded joints; (**b**) the smart joints with piezoelectric patches bonded to them [57].

4.1. Stress Control of Adhesive Bonded Joint Systems

In their proposal work, Cheng and Taheri [57,58] showed that the control over the stress concentration at the adhesive joints can be achieved through the use of the piezoelectric actuator and the induced surface moment. The electric field in the actuator is applied in order to maintain, or reach, a desired stress distribution within the adhesive layer. The locations of piezoelectric patches for possible bonding in their respective joints are presented in Figure 10b. Adhesively bonded single lap joints were explored by Khalili *et al.* [59] for their behaviour on the effect of piezoelectric patches. In their work, the authors demonstrated their methodology, based on the assumption that the shear stresses are characterized by shear lag and that the beam is on an elastic foundation. The authors presented an exposition of the joint edge peel and the adaptive control of the shear stresses that were done through the adjustment of the piezoelectric patches' electric field. It was also shown in their results that if the length of the patch is increased, then there would be a nonlinear change in the peel and the shear stresses.

The piezoelectric layers, on the other hand, were implemented by Cheng *et al.* [60–62] so that there is a gain in the reduction of stress effect concentration on a pipe system made up of adhesive composite materials. The piezoelectric layers were employed as sensors/actuators, and the pipe system was subjected to a load characterized by an axial tensile, bending, and torsion. The authors utilized the first-order shear deformation theory in deriving their criteria. The sketch below (Figure 11) portrays the configuration of the adhesive joint with a piezoelectric based reinforced layer.

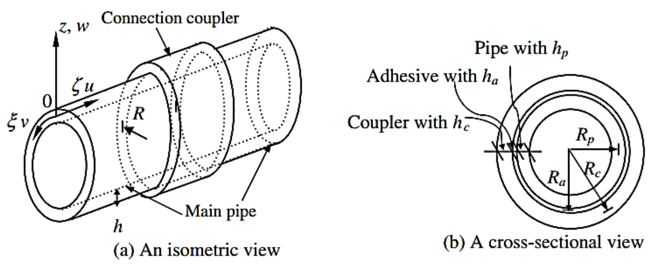


Figure 11. Schematic of adhesive joint with piezoelectric layer in coupler proposed by Cheng *et al.* [63].

The stress-transfer model of an adhesively bonded piezoelectric pipe-joint system was proposed by Bin *et al.* [63]. They investigated the effects of the adhesive layer on the shearing-stress distribution. The research results showed that the larger the thickness of the adhesive layer, the smaller the stress concentration that will be generated. On the other hand, it was discovered that the larger the shearing elastic modulus of the adhesive layer, the larger the stress concentration will be.

4.2. Stress Control of Edge Debonding

An analytical model of piezoelectric control was proposed in the work of Rabinovitch [64]. The model was presented in the context of beams that are strengthened by composite materials and developed for the control of edge debonding in the respective beams. This work was originally presented as a potential solution for the problem of failure in debonding and this was its main contribution goal. The work investigated various aspects of the problem including; analytical modelling, the strengthened beam's response to mechanical loads, and different plans of piezoelectric actuation. The investigation was done on the bonded composite strip and based on the localized stresses near its edge. Later on, the same author extended his work in [65], and through composite patches he gave the piezoelectric design optimization for the control of the edge-debonding failure in the reinforced beam, as well as the criteria for failure. Included in his work was the presentation of an optimization study based on numerical methods that reflected upon various piezoelectric actuator combinations in controlling the failure of edge-debonding. The author indeed gave a systematic approach to the piezoelectric control optimization based on the different criteria of debonding failure. The approach was also given to confirm the viability of applying the piezoelectric based system in a completed civil engineering structure.

5. The Effect of Bonding on Effectiveness of Active Control and Repair

When structures are bonded together based on piezoelectric patching, it is of significant importance not to ignore the effect of the layer formed through the bondage between the host structures and the piezoelectric actuators. This layer is of critical functionality that may influence the productiveness of the actuation in the context of the strain/stress transfer mechanism. In turn, this may well result in the wrong calculation of the required voltage for controlling the damaged structure.

An investigation regarding the piezoelectric based actuation and bondage for active repair on host structures using a boundary element method was carried out by Alaimo *et al.* [34]. The interfaces between the piezoelectric patches and the host structures were considered in terms of being perfect or imperfect. The study was conducted on the interfaces based on the repaired structure's properties in terms of the fracture mechanics. The active performance repair was noted to have been affected by the adhesiveness nature. This is due to the fact that, the imperfection of the interface between the host structures and the patch causes the piezoelectric patch's actuation capability to be lowered, as a result of lowered shear stress transfer by the adhesive effect.

In another work presented by Congrui *et al.* [66], the adhesive layer's geometrical and mechanical properties were studied. Their static effect on the load transfer was carefully examined. This load transfer was considered in the context of the piezoelectric actuator and a host medium of elastic form. The investigation was carried out for the edge, together with central debonding and including their respective composite structure's effect in stress distribution. It was implied from the authors' simulation results that the level of distribution for the shear stress within the internal part of the actuator would be elevated with the increase in the thickness of the bondage layer. In turn, the strain concentration at the actuator's tip would be lowered in the process.

Another analytical study was done by Liang *et al.* [67], based on the Timoshenko's theory of beams. This study explored the crack behaviour of an interface linking a piezoelectric actuator with an elastic substrate, at the same time taking the shear effect into consideration. The authors investigated straight cracks in a composite adhesive-based piezoelectric interface under a load influence of mechanical-electrical form. They presented stresses on the interface, as well as the straight crack's energy rates in Modes I and II. Alaimo *et al.* [68] investigated the skin/stiffener debonding and delamination cracks of laminated composite structures by applying the boundary element model. The multi-domain technique and the interface spring model were used to model the bonding between the host delaminated structure and the piezoelectric patch. To identify the debonding occurrence, the static and transient electromechanical response of the damaged structure with the bonded piezoelectric patch was studied.

6. Observations

The advance of piezoelectric materials opens up new opportunities for active damage repair and control techniques to suppress the onset and propagation of damage. In spite of its attractiveness, active repair is a very difficult problem, in both design and technological aspects. From the design point of view, active repairs and control of damaged structures can be, in fact, arranged by assembling piezoelectric actuators with the host damaged structures. This needs the development of analysis tools in order to understand the repair mechanism. The overall fracture mechanics behaviour of the repaired structures also needs these analysis tools.

From a literature review, it can be seen that most of the previous studies of the dynamic responses of piezoelectric coupled structures with open circuit electric boundary conditions were conducted with FEM simulations. It could be observed that the piezoelectric could not provide the accurate electric distribution along the thickness of the piezoelectric patches. Moreover, it is found that all previous repair methods using piezoelectric materials were applied mainly to thin beam and plate structures.

None of the existing research related to applications of piezoelectric actuators, in repair and control, have presented a clear numerical model in terms of damage onset and propagation in composite materials, but such an accurate model will help to understand the dynamic responses of structures bonded/integrated with piezoelectric patches. Another main observation is that there is no mathematical or numerical mode to provide an active feedback control repair method for the structural repair via piezoelectric materials for different damages on different structures.

Composite laminates were employed in more structural applications, therefore active repair and control for delaminated composites using piezoelectric materials by accurate criteria is required to characterize the laminate failure propagation.

The control of the stress concentration at the adhesive joints can be achieved through the use of the piezoelectric actuator and the induced surface moment. But there is no efficient and accurate experimental model to demonstrate the relation.

Most of the investigations on structural repair and stress control using piezoelectric materials were based on numerical simulations and analytical derivations, and only a few experimental studies were conducted. The urgency of the problem of increasing the fracture resistance of critical damage structures and their elements necessitates further investigation and development of new design solutions.

There is a discrepancy between the mechanics of material approach, which found that the crack/notch can be completely erased, while the fracture mechanics and boundary elements approaches found that the tip of the crack cannot be completely repaired by applying a piezoelectric actuator. The former approach is more realistic from the mathematical point of view, should the crack tip stress approach infinity at the crack tip.

Table 1 summarizes the methodologies used for active repair and control using a piezoelectric actuator with the main contributions and limitations.

Table 1. Key aspects of different methodologies used for active repair and control using piezoelectric actuator.

Reference	Methodology	Contributions	Limitations
[30,31]	Fracture mechanics	Active static repair of a cracked beam.	Only FEM simulation is proposed.
[33,34]	Boundary element method.	Active repair of a cracked structure using a piezoelectric patch.	No accurate analytical model to explain the repair process.
[45,46]	Euler–Bernoulli beam theory	An analytical model for the repair of a delaminated beam.	Applicable for static load only.
[28]	Resonant frequency of criterion.	An analytical model for a notched beam under dynamic loading.	The model gives the final result, no detailed information about the repair mechanism.
[53]	Boundary Element method	Active repair in the presence of frictional contact conditions.	Only FEM simulation is proposed.
[35]	Fracture mechanics	Statistical approach using Experimental and FEM simulation.	There is no analytical model to explain the repair process.
[37]	Slope discontinuity	Active repair of a notched cantilever beam subjected to dynamic loading. An accurate experiment and simulation model.	The result from the analytical model does not match the experimental result perfectly.

7. Conclusion

Active control and repair is a distinguished technique used for restoring the structural integrity of damaged parts. It is based on the converse piezoelectric, according to which the local moment/force induced by an applied electric field across the piezoelectric actuators can facilitate the structure to oppose known high stress/strain concentrations caused by the external load and, consequently, reduce the criticality of damage. Adhesively bonded joints are essential in the manufacturing of engineering structures. The failure of such adhesive joints normally happens prematurely, due to the presence of the stress concentration within the end regions of the adhesive interface bond lines. Therefore, it is desirable to reduce, or to control, the amount of such stress concentration, which will lead to improving the joint's stiffness.

In this review, guidelines are established for researchers who would like to use piezoelectric actuators in engineering structures. These guidelines are: classification of piezoelectric actuators applications, observations and critical literature review. The classification can provide a brief idea of the research areas involving piezoelectric actuators. Moreover, the observations and the essential literature review can offer researchers a transparent vision and indications for the research space that they must target. In summary, these guidelines can facilitate the means for researchers, particularly within the early steps of this subject to come up with new ideas.

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Conflicts of Interest

The authors declare no conflict of interest.

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