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Restoration of Natural Frequency and Structural Stiffness in Cracked Aluminum Flexible Beams Using Epoxy–Composite Patch Repair: Experimental Study

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Abstract

A complete experimental research study, with the aid of analysis interpretation by Euler-Bernoulli beam relations formulas, was conducted to explore the impact of bonded repairs with epoxy-glass composite patches on the dynamic properties of the cracked aluminum Flexible Beams. The components were fabricated to undergo stiffness loss due to crack damage and explore the repairs caused by the application of one- and two-sided bonded epoxy-glass composite patches. A miniature version of the beam model simulating the shape and form of a Flexible Beam was tested over four stages - with and without damage and repairs. The results showed that stiffness loss was 4.4% due to the 13.5 mm crack damage; however, almost 98% stiffness restoration was restored by one-sided bond application with one and two-sided application of the epoxy-glass patches. The outcome confirms that applying one- and two-sided bond applications with the use of epoxy-glass patches is significantly effective as an efficient solution with minimal weight to restore cracked Flexible Beams.

Keywords: bonded composite patch; epoxy adhesive; stiffness recovery; modal testing

I. Introduction

The Flexible Beams are subjected to very high centrifugal, thermal, and vibratory loads in power-generation turbines. Root or mid-span sections of the blades are very susceptible to fatigue crack formation, causing a stiffness reduction that can lead to catastrophic resonance phenomena [1]. Conventional repair techniques, like welding or riveting, may introduce residual stresses or alter mass distribution and, therefore, are not suitable for thin-walled, high-speed components [2]. One practical solution developed involves the use of adhesively bonded composite patches that permit local reinforcement with minimal weight penalty and without compromising aerodynamic balance.

Bonded composite patch repair has been widely used for structural restoration of metallic and composite components [3]. The early analytical models by Rose [4] and Baker [5] described SIF reduction under bonded reinforcement and provided the basis for modern patch design.

Experimental work by Nahas and Sharma et al showed that patches could restore the first natural frequency of cracked aluminium beams to nearly intact values. Ewins and Rao established that a structure's natural frequency varies with the square root of its flexural rigidity (EI), making modal frequency a direct indicator of stiffness. This forms the theoretical basis of the stiffness recovery analysis done in this paper. Recent studies conducted by Adeela Nasrin [6] and Orsatelli et al. [7] have further highlighted the dual role of adhesives: restoring stiffness while contributing damping through viscoelastic behavior.

The contribution of this work is the experimental validation of epoxy–glass patches applied on turbine-blade-like aluminium sections through modal testing and the correlation of stiffness with frequency to judge repair efficiency. The effective stiffness is calculated as per classical beam vibration theory, and the amount of recovery can be quantified by linking experimental data to mechanical behavior.

II. Experimental Program

The experimental program was designed to study the effects of composite patch repairs on the dynamic behavior of cracked aluminium beams. The procedures and specimen configurations were developed to ensure consistency, and also to replicate, as closely as possible, the mechanical boundary conditions of Flexible Beams in service. Details related to the specimen geometry and setup are given in the following subsection [8].

II.i Specimen and Geometry

The aluminium beams were machined to represent simplified Flexible Beam sections: overall dimensions are 160 mm in length, 45 mm in width and 1mm in thickness. The beams were rigidly clamped at one end to simulate the Flexible Beam root constraint. The effective free length was approximately 135 mm. This configuration provides a realistic cantilever boundary condition representative of the actual turbine-blade behavior under vibratory loading. Cracks were produced by using a wire-cut EDM process [9] in order to obtain an accurate measurement without residual stress. Each crack was 13.5 mm [10] long and approximately 0.25 mm wide, located 27 mm from the fixed end (20% of beam length [11]).

II.ii Patch and Adhesive Properties

The repair patch consisted of a five-layer glass/epoxy laminate with fiber orientations of 90° relative to the beam axis. The adhesive was a 50/50 blend of UHU 2-K-Epoxidkleber Binder (1.2 gr/ml) and UHU 2-K-Epoxidkleber Hardener (1.13 gr/ml), chosen for high shear strength and compatibility with aluminium.

Table 1. Used Materials Properties [12]

Property	Aluminium	Glass-Epoxy
Elastic Modulus (GPa)	70	240.27
Density (gr/cm^3)	2.7	1.65
Ultimate Strength (MPa)	310	1811.21

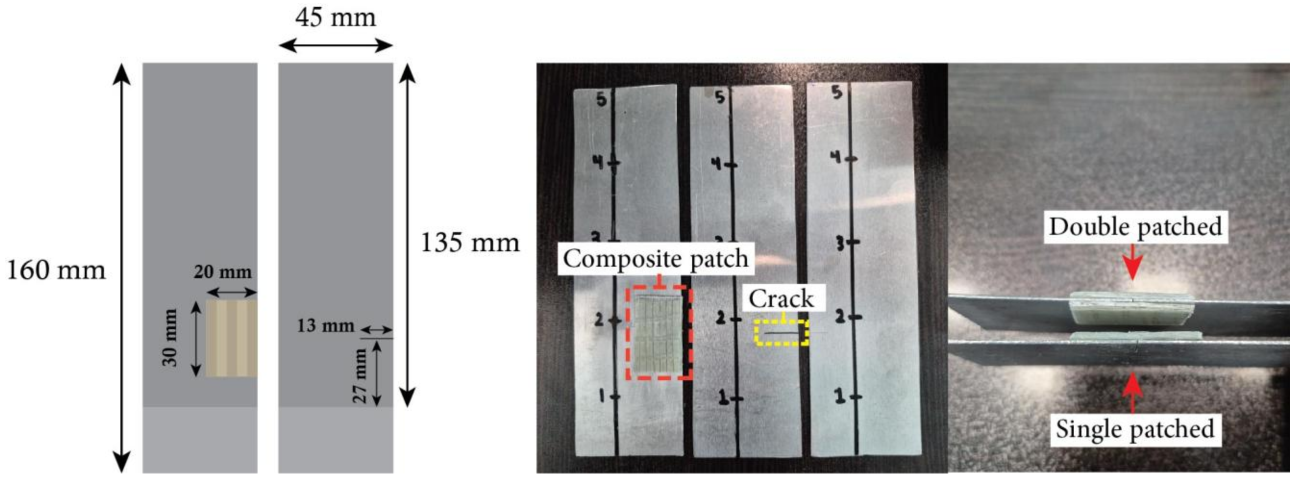

Figure 1. Constructed Test Beds

The surface preparation was carried out as follows:

The aluminum surface was successively sanded with 100, 180, 240, 320, and 400-grit in two perpendicular directions, then alkaline cleaning was carried out in warm water (about 70 °C) for 10 minutes and followed by acetone degreasing. The composite patch was bonded to the aluminum surface with the aid of Araldite 2015 adhesive with about 50 kPa pressure for 20 minutes during the curing process [13].

II.iii Modal Testing Setup

Excitation was applied by an impact hammer at a distance of 0.25 L from the fixed end. Acceleration responses were recorded by three accelerometers mounted at 0.5 L, 0.75 L, and L. The frequency response functions (FRFs) were acquired using a Spider-80X Dynamic Measurement System (Crystal Instruments, USA). Each test was repeated three times to ensure measurement repeatability.

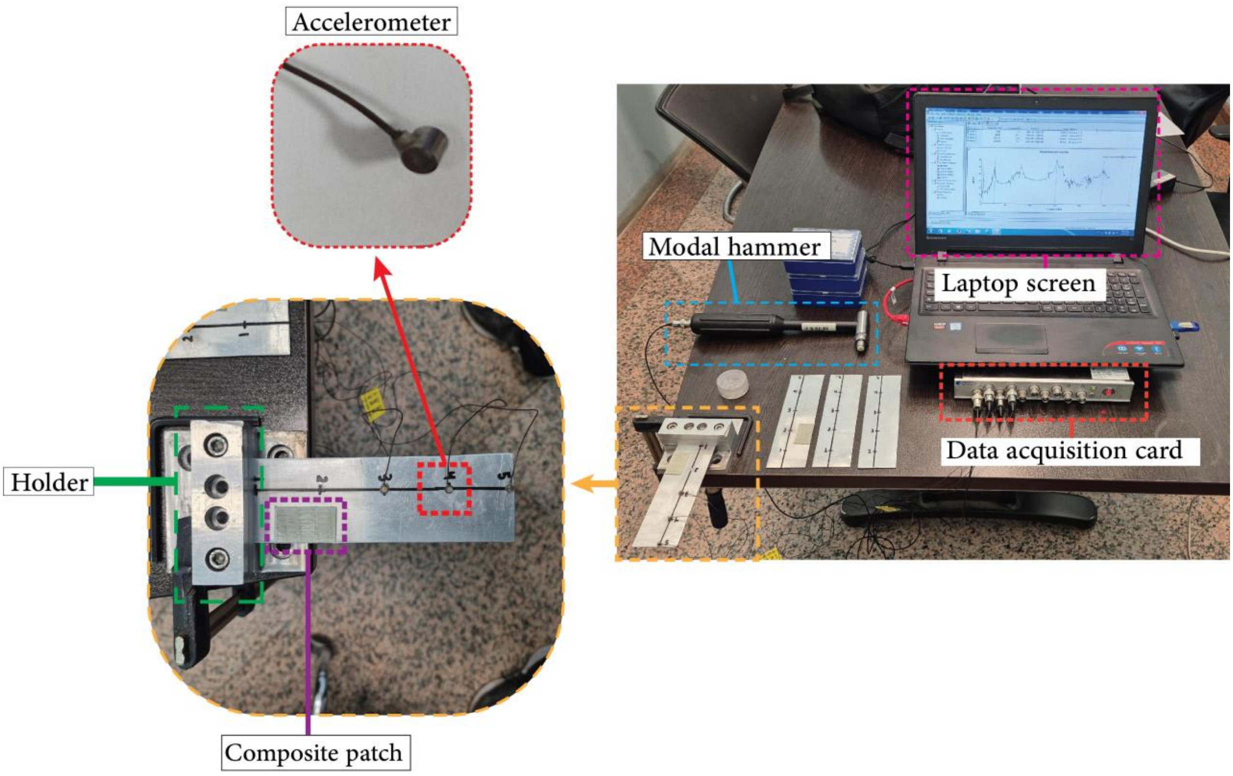

Figure 2. Experimental Setup

III. Estimation of Frequency and Stiffness Recovery

An analytical methodology has been developed that interprets the experimental observations in terms of the required variation in structural stiffness for the measured changes in vibration frequencies. Such an analysis represents a relatively simple but effective technique for quantifying both the amount of stiffness degradation due to cracking and the recovery realized using patch repairs.

For an Euler-Bernoulli cantilever beam, the first natural frequency is:

$$f_1 = \frac{1}{2\pi}\beta_1^2\sqrt{\frac{EI}{\rho A L^4}} \quad (1)$$

Where $\beta_1 = 1.875$. Equation (1) shows that f_1 is proportional to $\sqrt{EI}$, so relative stiffness can be estimated from frequency ratios:

$$\frac{(EI)_x}{(EI)_0} = \left(\frac{f_x}{f_0}\right)^2 \quad (2)$$

This relationship forms the basis of many vibration-based stiffness-identification methods, and is widely used in bonded repair assessment. substituting into Eq.(2) the corresponding stiffness ratios were obtained as:

$$\frac{EI_c}{EI_0} = 0.914, \quad \frac{EI_s}{EI_0} = 0.984, \quad \frac{EI_d}{EI_0} = 1.267.$$

It could recover almost the lost bending stiffness by a single-sided patch, reaching about 98.4% of the intact beam value. This corresponds to an 81.3% recovery of the lost stiffness due to cracking. On the other hand, the double-sided patch compensated for the damage and increased the stiffness by approximately 26.7%, bringing about an overall stiffer structure.

Table 2. Stiffness ratios estimated from experimental vibration data using analytical relations

Condition	Frequency (Hz)	EI/EI_0	Comment
Intact	41.92	1.000	Baseline
Cracked	40.07	0.914	8.6% stiffness loss
Single Patched	41.58	0.984	98.45% of original stiffness
Double Patched	47.19	1.267	Over-stiffened (+26.7%)

The proportionality in equation (2) shows that the dynamic stiffness is proportionally independent of the frequency of the modes. Small variations in the vibration frequencies can therefore be an indicator that stiffness has changed due to damage or repairs. The following is the theoretical explanation that verifies that bonding with epoxy and glass has mainly restored stiffness without introducing excess stiffness through added weight and dampers, and therefore works well with the mode testing principles suggested by Ewins [14].

III.i Results and Discussions

In this section, the results from the experimental study are presented and analyzed with the use of theoretical relations between frequency and stiffness. These results are analyzed in relation to frequency change, stiffness recovery, and dampening capacity before presenting implications and recommendations. In effect, there is a critical analysis presented in this study to evaluate the efficacy of single- and double-sided composite patch repairs in improving the dynamics of cracked aluminum beams. Table 3 below provides the results derived from the experimental study conducted to obtain the natural frequencies and dampening ratios of the various beam configurations.

Table 3. Experimental natural frequencies and damping ratios

Category	f_1 (Hz)	Damping (%)	Relative Stiffness
Healthy	41.92	1.04	1
Cracked	40.07	0.74	0.91
Single patched	41.58	1.13	0.98
Double Patched	47.19	1.46	1.267

The presence of a 13 mm crack reduced the first bending natural frequency by 4.4%, implying a calculated stiffness loss of about 8.6%. The single-sided composite patch successfully recovered the frequency within 1% of the intact beam, representing approximately 98% recovery of the original stiffness. Conversely, the application of the double-sided patch resulted in the increase of the natural frequency by 12.6% compared to the baseline, confirming that an important stiffening over-compensation occurred, as actually predicted by the analysis.

A clear trend was also reflected in the damping behavior: the cracked beam had a noticeable drop in damping, from 1.04% to 0.74%, which may be associated with the discontinuity of material and hence reduced internal energy dissipation. The two repaired configurations exhibited considerable increase in damping upon repair, reaching 1.13% for the single-patch and up to 1.46% for the double-patch configuration. This improvement is believed to be due to viscoelastic energy dissipation within the adhesive layer and interfacial shear between the patch and the aluminum substrate.

This increased damping, while helpful for vibration attenuation and the improvement of fatigue resistance, still remains moderate enough not to alter the overall dynamic behavior of the original structure. These results confirm that composite patching not only restores the stiffness but also beneficially modifies the system's damping characteristics, thus providing mechanical and vibrational improvements.

III.ii Engineering Implications

In large-scale structures, such as Flexible Beams, local stiffness variations may strongly influence resonance and balance. In the current study, experimental results indicated that single-side composite patching effectively restored stiffness, preserving the original modal frequencies, ideal for vibration-critical repairs at the laboratory scale. However, in real turbine components, where dimensions and loading conditions are usually more complex, the additional structural integrity and fatigue resistance of double-sided reinforcement may be valued. In these full-scale applications, the relative increase in stiffness due to double patching may indeed become less pronounced, with possibly negligible consequences on dynamic imbalance or flutter behavior. Consequently, the optimum repair configuration should be chosen by taking into consideration both the requirements of vibration sensitivity and operational demands.

IV. Conclusion

The present study sought to investigate the efficacy of different composite patches to restore the stiffness and dynamics of cracked aluminum beam models simulating Flexible Beams. A comprehensive experimental study was conducted with theoretical equations to analyze the results in terms of frequency responses and stiffness recovery for single- and double-sided repairs.

In terms of application, one-sided patching may be seen as a light and efficient solution to critical vibration suppression in rotating components and boiler shells. In these application areas, if the fundamental frequency is decreased, there might be resonance phenomena; therefore, raising the fundamental frequency above the rotor speed becomes essential. This requirement is met efficiently by one-sided patching techniques in cracked beam components. If more robust dynamics are demanded within these areas, two-sided patching becomes more useful to improve fatigue resistance and stiffness. The increased damping in these patched configurations again highlight the energy dissipation that occurs within the adhesive layers and interlayers that assist in vibration suppression.

In conclusion, the findings below explicitly confirm the effectiveness of composite patching as a rapid, lightweight process to efficiently mend metallic parts that are dynamically loaded. The integrated research methodology with correlation analysis encapsulated within this research study offers credible rationale to establish predictive models in stiffness recovery during repairs to Flexible Beams. Further research is suggested to be conducted on fatigue models and full-scale components.

REFERENCES

1. Fernandes, R., El-Borgi, S., Ahmed, K. *et al.* Static fracture and modal analysis simulation of a gas turbine compressor blade and bladed disk system. *Adv. Model. and Simul. in Eng. Sci.* 3, 30 (2016)
2. Dada, M., et al., "Recent advances in joining technologies of aluminum alloys: a review" *Journal of Materials Research and Technology* (Springer review), (2024)
3. A. Aabid, M. Hrairi, J.S.M. Ali, T.A. Sebaey, "A Review on Reductions in the Stress-Intensity Factor of Cracked Plates Using Bonded Composite Patches", *Materials*, vol. 15, no. 9, Article 3086, 2022.
4. Rose, L.R.F. "A cracked plate repaired by bonded reinforcements." *Int J Fract 18*, 135–144 (1982)
5. Baker Ph.D., A.A., et al. "Advances in the Bonded Composite Repair of Metallic Aircraft Structure." Netherlands, Elsevier Science, (2003)
6. Jean-Baptiste Orsatelli. Et al. "Bonded flush repairs for aerospace composite structures: A review on modelling strategies and application to repairs optimization, reliability and durability" *Journal of Composite Structure* 304, 116338
7. Adeela Nasreen. Et al. "Effect of Surface Treatment on Stiffness and Damping Behavior of Metal-Metal and Composite-Metal Adhesive Joints" (2023)
8. Samir Lecheb. Et al. "An Advanced Dynamic Repair of Edge Crack Aluminum Plate with a CompositePatch" *Materials Science Forum* (Volumes 794-796) 716-721 (2014)
9. Kumar P, Shinde PS, Pawar K. A model to predict fatigue crack initiation in plates with a pre-crack. *Strength, Fracture and Complexity*. (2018)
10. Siva Sankara Babu Chinka, Srinivasa Rao Putti, Bala Krishna Adavi, "Modal testing and evaluation of cracks on cantilever beam using mode shape curvatures and natural frequencies" *Structures*, Volume 32, Pages 1386-1397, (2021)
11. Mahmoud Nadim Nahas, Mahmoud Ali Alzahrani, "Restoration of Natural Frequency of Cracked Cantilever Beam Using CNT Composite Patch: A Finite Element Study" (2013)
12. Hossein Nadi, Mojtaba Haghighi-Yazdi, and Majid Safarabadi, "Experimental and Theoretical Investigation of the Effect of Fiber Orientation Angle on the Flexural Strength of Glass/Epoxy Composites to Find the Transient Angle" (2024)
13. Hosseini, K., Safarabadi, M., Ganjiani, M., Mohammadi, E., & Hosseini, A. "Experimental and numerical fatigue life study of cracked AL plates reinforced by glass/epoxy composite patches in different stress ratios." *Mechanics Based Design of Structures and Machines*, *49*(6), 894–910. (2020)
14. D.J. Ewins, "Modal testing: theory, practice, and application." United Kingdom, *Wiley*, (2000)