Integration of eddy current sensors into repair patches for fatigue reinforcement at rivet holes

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Abstract
Fatigue cracks at rivet holes occur at advanced service life of aircrafts due to cyclic loading. As a repair method, adhesively bonded stiffener patches enhance the fatigue life of the structure by delaying crack initiation and reducing crack growth. Combining a crack sensor with a repair patch to a sensor-based stiffener patch allows crack growth reduction and monitoring at the same time. This paper presents a feasibility study on the integration of eddy current sensors into carbon fibre reinforced plastic (CFRP) repair patches. To this end, a specific patch design is developed, and samples are manufactured by ultrasonic fabrication. The performance of the patches is investigated in fatigue tests in terms of ‘crack reinforcement’ and ‘crack detection.’ Both requirements are met. The undertaking of future efforts to tailor the sensor-based repair patch concept to an individual application in aircraft maintenance seems reasonable.

KEYWORDS
CFRP repair patch, eddy current testing, fatigue reinforcement, structural health monitoring, ultrasonic processing

1 INTRODUCTION
Rivet holes in metallic structures that are subject to cyclically varying mechanical loading are prone to fatigue cracking. In aircraft structures, a multitude of rivet holes exist that have to be checked for cracks regularly. During maintenance checks, accessibility can be difficult as other parts might have to be removed which can result in long and costly aircraft downtimes. Thus, a reliable continuous crack monitoring system can help to reduce maintenance costs and efforts.

Under certain conditions, cracked components can be repaired, usually by applying a riveted or bolted metallic doubler. Another solution to enhance the fatigue life of cracked components is the use of adhesively bonded stiffeners made of fibre reinforced plastics (FRPs). Compared to conventional repair methods, the so-called metallic crack patching has the advantage that the cracked structure is not subject to additional weakening caused by drilled holes.

The idea now is to combine the crack sensor with a stiffener patch. This way, holes that tend to fatigue cracking can be supported, crack initiation can be delayed, and crack growth can be reduced and monitored at the same time. To
find a suitable sensor system that can be combined with or included in bonded FRP patches, a number of requirements need to be defined. From a practical as well as from an economical point of view, these requirements result to be

- dependable crack length measurement,
- producibility combined with an FRP doubler,
- applicability to variable environmental conditions,
- fast data collection,
- easy to apply and to read out,
- suitable durability,
- low sensor development costs,
- low sensor unit costs.

One sensor concept that satisfies the requirements defined is the eddy current sensor (ECS). Winded in a flat coil, it can be combined with FRP materials, for instance carbon fibre reinforced plastics (CFRPs), and applied to a rivet hole in form of a sensor-based stiffener patch.

This paper presents a first feasibility study on the use of sensor-based CFRP patches (hereinafter abbreviated RSP, repair sensor patch), using an ECS. An overview of current crack monitoring technology is given in Section 2, followed by a detailed description of the working principle of the proposed RSP conceptual design in Section 3. A suitable production technology, namely, the ultrasonic fabrication of CFRP, is evaluated in Section 4, and a first proof-of-concept on coupon test level in Section 5 shows the effectivity in crack detection.

### 2 | STATE OF THE ART CRACK MONITORING

With 13 % of the overall operating costs, aircraft maintenance costs are one of the driving cost factors in aircraft service (in comparison, the overall fuel costs are about 17%).[1] Reducing aircraft downtimes and delaying periodic service inspections can therefore significantly reduce aircraft operating costs. Further, the exchange of structural parts after a defined service life without considering its structural integrity is not sustainable. Here, the need for a monitoring system arises that is capable to continuously monitor the component’s condition. Such monitoring systems are often referred to as condition or structural health monitoring.[2] Providing the reliable long-term functionality of the sensor system, the continuous monitoring of components with limited accessibility can help to reduce costly inspection procedures as the status of the component’s integrity can be read out directly from the sensor system and does not need expensive maintenance measures. Demand-oriented service procedures are the next big step towards the reduction of aircraft downtimes; thus, the evaluation of different monitoring systems is one of the crucial tasks in today’s research.[3–6]

Bonded FRP repair patches are known to reduce crack growth rates compared to the unstiffened component.[7] They are either used in a repair functionality (application after crack initiation) or in a stiffener functionality (application to endangered components before cracking). Patch disbond, which is mainly induced from the patch boundaries, leads to a fast reduction of the repair functionality; thus, monitoring the adhesive bonding in the outer patch region is of great interest.[8,9] In contrast, here the focus is set on crack length measurement for crack endangered components. Thus, the area close to the hole is the critical here and has to be monitored.

Several different approaches for ‘smart patches’ with integrated condition monitoring can be found in literature.[10–13] Also a number of U.S. patents exist that include different sensor techniques to monitor the repair integrity.[14–17] Ihn et. al.[18,19] used piezoelectric actors and sensors to measure the crack length, integrating them into an additional ‘smart layer’ between cracked structure and FRP repair patch. A similar approach is followed by Ahmed et al.[20] who used a carbon nanotube-based sensing layer. Other crack detection methods are based on strain changes or resistance changes of an electric circuit interrupted by the crack.[21–23] In contrast to the above-mentioned methods, eddy current testing does not require a direct contact between ECS and crack because a small lift-off is tolerable. Offering the possibility to install the sensor on top of the repair, patch and bond may be optimised for their original load carrying function.

The use of ECS is common practice in aircraft maintenance for the inspection of cracks underneath other components.[24,25] But not only inspection, also damage monitoring using ECS has proven to be effective. For instance, Jiao et al. showed the possibility of fatigue crack detection in flat metallic structures with a resolution of 1 mm, using a planar ECS.[26] The combination of a planar, rectangular ECS with a non-conductive repair patch on carbon steel was analysed for instance by Roach et al.[27] Tsamasphyros et al.[28] and Marioli-Riga et al.[29] examined leave-in-place ECS
for crack monitoring under boron composite patches on single edge cracked aluminium specimens. The non-conductive repair patch can be seen as a lift-off for the ECS that might decrease the resolution and quality of the crack length measurement. A more comprehensive study on examining appropriate properties for a suitable crack length resolution is described in Tsamasphyros et al.\[28\]

Knowing that the use of ECS in combination with non-conductive patches is possible in principle, the question arises as to whether this approach is sensible to tackle the specific challenge of fatigue cracks at rivet holes. Here, the ECS is installed on top of a circular CFRP repair patch, and crack length is measured under fatigue loading of centre cracked aluminium specimens. The goal is to reconcile fatigue reinforcement with crack propagation measurement in a single sensor-based repair patch.

To this end, a suitable production technique needs to be found that is able to join the ECS with the composite patch. Here, the method of ultrasonic welding is used, which was described in depth by Gomer et al.\[30,31\] This method is advantageous as it has short cycle times and allows patch manufacturing from raw carbon fabric and polymer film. Compared to conventional base materials such as prepregs or epoxy resin, these materials are harmless to health and less demanding in terms of storage conditions.\[32,33\] Disadvantageous is the limitation to thermoplastic matrix materials, which have poor mechanical properties compared to thermoset materials.\[34\]

3 | STIFFENER PATCH DESIGN

The principle composition of a bonded CFRP patch around a rivet hole for a protruding rivet head is shown in Figure 1a.

Usually, the metallic sheet is covered with a corrosion inhibiting primer that also promotes the bonding between the metallic and the composite components. The adhesive layer joins the metallic structure and the reinforcing patch. The full functionality of the reinforcement is only fulfilled for a proper and uniform bonding. Any inaccuracy, especially local disbonds, leads to reduced properties. Thus, from a mechanical point of view, the best position for an ECS is on top of the patch; see Figure 1b.

Within this work, one specific configuration of this design pattern is developed and tested as a proof-of-concept. From a technical perspective, there are no indications that other adaptations of RSP with an integrated ECS should not be feasible. These adaptations may include different manufacturing processes or varying patch and coil dimensions. The right choice has to be assessed for the individual purpose.

3.1 | Challenges

Apart from the main premise of an unobstructed reinforcement functionality, there are three key factors that constrain the RSP development: firstly, the physical requirements to obtain a sufficient sensor signal for crack detection; secondly, the limitations set by the ultrasonic fabrication process; and lastly, the specimen geometry as the specific use case.

3.1.1 | Functional principle of an ECS

In an eddy current measurement, the objective quantity is the impedance of a sensor coil. The underlying physical principle is outlined schematically in Figure 2. An alternating current $I_0$ flowing through a coil develops an alternating...
magnetic field $H_0$ surrounding the coil. If a conductive material, such as aluminium, is present in the magnetic field, eddy currents $I_{EC}$ are induced in this material. The eddy currents follow a circular path and generate a secondary magnetic field $H_{EC}$, which opposes the primary field according to Lenz’s law.[35] Due to the interaction of the currents and magnetic fields, the impedance of the coil changes. This change in impedance is detected by recording current $I_0$ and voltage $U_0$ at the coil. The impedance of an ECS typically varies depending on changes to

- the electrical conductivity and magnetic permeability of the sample material,
- the lift-off from the surface $h$,
- the orientation of the sensor,
- the amperage and the frequency of the current, and
- environmental factors, such as temperature and pollution with conductive material.

If a crack develops in the material, schematically shown in Figure 3, it physically represents an obstacle to the eddy currents and the electrical resistance of the sample increases. The increased resistance leads to a weakened secondary field $H_{EC}$, which has less effect on the primary field $H_0$. Consequently, the measured inductance of the coil rises with increasing crack length and moves towards the value it would have in pure air.[37] The measurability of the crack is highest when its orientation is perpendicular to the path of the eddy currents and the coil is as close to the sample material as possible.[38] Since a zero lift-off is in conflict with the reinforcement properties of the patch, the minimum lift-off is equivalent to the thickness of CFRP layer.

### 3.1.2 Ultrasonic fabrication of CFRP

For the ultrasonic fabrication of CFRP, the carbon fibres are rolled off from a roving or a fabric roll, and the thermoplastic resin is given as a polymer film from polyamide 6 (PA6). Fibres and matrix are welded into a laminate by an ultrasonic welding machine in a single process, which can be broken down into five steps for easier description.[31] For the preparation of the process, fibres and matrix foil are stacked in layers (for the sake of simplicity one layer in
Figure 4a). The horn moves down onto the stack and compresses it (see Figure 4b). After reaching a predefined trigger force $F_{\text{Trigger}}$, the ultrasonic welding begins (see Figure 4c). Carbon fibres and polymer films are excited to vibrations by the horn of the ultrasonic welding machine at 20 kHz in vertical direction. Molecular and interfacial friction is generated, resulting in heat generation, melting the thermoplastic films. The fibres are enclosed by the polymer melt pushed in by the welding force $F_{\text{Weld}}$. After the predefined welding time $t_{\text{Weld}}$, the oscillation is stopped, and the holding step starts (see Figure 4d). A pressure force $F_{\text{Hold}}$ is retained during this step, allowing the heat to dissipate into horn and anvil. The polymer solidifies, resulting in a CFRP laminate. The sample is retrieved after moving the horn upward (see Figure 4e).

The main parameters characterising the ultrasonic fabrication process are welding force $F_{\text{Weld}}$, welding time $t_{\text{Weld}}$, the amplitude of the ultrasonic vibrations $A$ and thicknesses and number of polymer layers and canvas. Besides these, trigger force $F_{\text{Trigger}}$, holding force $F_{\text{Hold}}$ and holding time $t_{\text{Hold}}$ influence the welding result. If the dimensions or types of polymer foils and canvas are changed, especially $F_{\text{Weld}}$ and $t_{\text{Weld}}$ need to be adapted by trial and error experiments.

The ultrasonic fabrication of CFRP is chosen within this work due to its availability, its short cycle times and its suitability for a future automation.[39]

### 3.1.3 Specimen geometry

Coupon fatigue tests for the application of rivet holes can be performed with centre cracked tension (CCT) specimens. The final specimen design used within this work has been developed to fit the internal test bench and has proven to be suitable in past experiments. It is depicted in Figure 5 and has a length, width and thickness of $l = 220$, $w = 70$ and $t = 3\text{mm}$, respectively. The rivet hole has a radius of $r = 2\text{mm}$ and crack starter notches of 2 mm each at both sides.
brought in by sawcut. Thus, the total tip-to-tip initial crack length is \( 2d_0 = 8 \text{mm} \). The dimensions were chosen for an exemplary semi-tubular pan head rivet with a nominal diameter of 4mm described in DIN standard 6791. \(^{[40]}\)

### 3.2 Patch design for feasibility study

The RSP particularly designed for this proof-of-concept is schematically shown in Figure 6, followed by a photography of a fully assembled RSP in Figure 7.

A broad CFRP ring patch stiffens the structure in order to reinforce the metallic structure. The ECS is mounted directly on top of the patch in order to minimise the distance to the metallic component. An additional component is required to protect the ECS from damage during the ultrasonic welding process and to fix it at its position radially. In the given case, a second, narrow CFRP ring patch is used. The narrow CFRP ring patch is not specifically designed to have an impact on the repair properties but is chosen to further exploit the opportunities that the ultrasonic fabrication of CFRP offers. In this light, the additional layers of carbon fabric and PA6 film are brought in to facilitate the bonding of the CFRP ring patches by ultrasonic welding. The upper PA6 film also fixes the ECS at its position vertically.

Dimensions of the RSP components are depicted in Figure 6. The inner diameter of \( d = 8 \text{ mm} \) corresponds to the diameter of a rivet head, and the outer diameter is limited to \( D = 40 \text{mm} \) by the specifications of the ultrasonic welding machine. However, it is sufficiently large to have an effect on the lifetime of the specimen.

The choice of a flat coil without bobbin is driven by various reasons. A single absolute coil is the less intricate mode of design for an ECS. This is considered sufficient for a proof-of-concept. With the positioning of the coil, an alignment of the axis of rivet hole and coil is achieved, so that a crack running radially from the rivet hole is perpendicular to the eddy currents, which increases the probability of crack detection. The flat design with a height of 0.5 mm complies with the overall requirement of the CFRP patches to follow the surface curvature. This limits the number of possible wire layers and accordingly the total number of windings. This limitation can be compensated to a certain extent by the...
choice of a smaller wire diameter of 0.05 mm. The inner diameter of the coil is chosen corresponding to the rivet head; the outer diameter allows for the below described manufacturing procedure (see Section 4). All other coil parameters result from this limitation and are presented in Table 1. It should be noted that the choice of a different manufacturing process may omit the need of the upper narrow CFRP patch and allows an extension of the sensor coil up to the edge of the patch.

4 | PATCH MANUFACTURING

The ultrasonic fabrication of CFRP is used for both the assembly of the RSP and the manufacturing of its components. All manufacturing steps are carried out on an ultrasonic welding machine of the type HiQ DIALOG 6200 from Herrmann Ultraschall GmbH & Co. KG, Karlsbad, Germany, which works on an ultrasonic frequency of 20 kHz.

4.1 | Production of components

A full circular ring patch laminate is the starting point for either of the two CFRP components of the RSP (see Figure 9). It is manufactured on a 41-mm diameter elevated tool (see Figure 8a), whose purpose is to reduce the welding area to the required circular shape. Commencing the component production, a square piece of PA6 film with an edge length of 66 mm is fixed to the tool holder with adhesive tape. This is followed by a piece of carbon fabric measuring 50 × 50 mm which is fixed by two further layers of PA6 film. Due to the additional interfaces, more friction is generated in a double layer of polymer film than in a single layer of twice the thickness.[31] Alternately, one layer of carbon fibre fabric and two layers of PA6 foil are applied. A single layer of PA6 film is used at the top. The total number of carbon fabric layers is 5 which is the maximum number of layers for which repeatability is achieved without exceeding the machine capabilities.

The stack of PA6 and carbon fibre fabric is now processed into a laminate in a single ultrasonic welding operation with the parameters given in Table 2. The impression of the tool is clearly recognisable in Figure 9. In a last step, both ring patches are brought into their final shape with a punching tool (see Figure 10).

| Parameter        | Value   |
|------------------|---------|
| Inner diameter   | 8.4 mm  |
| Outer diameter   | 20 mm   |
| Height           | 0.5 mm  |
| Wire thickness   | 0.05 mm |
| Number of turns  | 700     |
| Resistivity      | 270 Ω   |
| Inductivity      | 7.4 mH  |

Table 1 Geometric and electric properties of the sensor coil

(a) Circular laminate tool

(b) Assembly tool

Figure 8 Cross-sectional view of the rotation-symmetric tools used for patch manufacturing: (a) elevated tool for circular laminate production; (b) assembly tool with cavity to spare the sensor from ultrasonic vibrations
In a further welding process, the individual components are joined together to form the finished RSP. In preliminary tests, the ECS turned out to be very vulnerable and was destroyed as soon as it was directly subjected to ultrasonic vibrations. Hence, another tool is used that holds the components in their position during the welding process (see Figure 8b). The tool also provides a cavity under the base area of the ECS, to prevent the force of the ultrasonic fabrication process from running through the ECS. To connect the broad and the narrow CFRP ring patch with each other, two additional PA6 films and a layer of carbon fibre fabric are required. Given this additional material interfaces, enough friction is generated to melt the polymer and join the ring patches to a RSP. The assembled but not yet processed RSP is depicted in Figure 11.

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Following the welding process, the final RSP, which is depicted above in Figure 7, is obtained by removing the protruding film and carbon fibre fabric with a pair of scissors. All RSPs tested in the subsequent section were fabricated as described in this section.

5 | FATIGUE TESTS

The fatigue tests carried out in this section are intended to test the above described RSP for two properties: the repair effectiveness and the crack detection effectiveness. The number of specimens tested with RSP is \( n = 12 \). The same amount of specimens without RSP is tested as a comparative group.

5.1 | Specimen preparation

All aluminium samples receive the same pretreatment to ensure comparability and not to undesirably distort the results by mechanical or thermal treatment. The assignment of RSP to aluminium samples is random; the same applies for the sequence in which the RSP are bonded to the specimen.

A rough, clean and grease-free surface is necessary for the bonding. For surface pretreatment, the samples are sandblasted with corundum used as blasting medium. The surface of the RSP is slightly roughened with sandpaper. All bonding surfaces are cleaned of dust and grease in two steps with isopropanol and acetone. The two-component adhesive used is 3M Scotch-Weld EC-9323 B/A. The adhesive is certified for aerospace applications and is suitable for structural joints between plastics and metals due to its high mechanical strength. The thickness of the adhesive layer is approximately 0.2mm. The adhesive is cured for 2h at 65°C in an oven. All samples receive thermal treatment, including the comparative group without RSP.

5.2 | Experimental procedure and testing equipment

Three samples without RSP and three samples with RSP are tested alternately. The selection of the sample is random. Each fatigue test is continued until the specimen breaks.

5.2.1 | Testing machine and load

The fatigue tests are carried out force controlled on a Schenck POZ 160 hydraulic tensile testing machine from Carl Schenck AG, Darmstadt, Germany. The forces correspond to the stresses given in Table 3.

A clamped sample is shown in Figure 12. The connection wires are fixed on the specimen with adhesive tape, to protect the sensitive solder joints during fatigue testing.
During the tests, the cyclic load is automatically interrupted to generate a load sequence with static loads at maximum, minimum and mean stress, each for a period of 5 s. Purpose of the interruptions is to determine, whether the ECS is able to detect cracks even at standstill or with partial tension relief. After the interruption, the cyclical load continues automatically. The first intermediate sequence starts after 11,500 load cycles, followed by further intermediate sequences after 2000 load cycles each.

### 5.2.2 Reference measurement with infrared camera

Reference measurements of the crack length are carried out by infrared thermography.\textsuperscript{[41,42]} The thermographic camera ImageIR 8380 S from InfraTec GmbH, Dresden, Germany is used. The backs of the samples are painted black to avoid reflections during the reference measurement. For a stronger contrast, a cooling battery is hung up in the background. Thermal images are captured every 2000 load cycles. The crack length is determined by employing the thermal imaging software IRBIS 3 professional, where specimen width and distance between heat dissipation areas are manually marked as reference length and as tip-to-tip crack length, respectively. The accuracy of the crack measurement is limited (±1 mm) but serves as a rough estimate and to detect potential errors in the experiment (e.g., asymmetric crack growth).

### 5.2.3 Sensor coil signal tracking

The sensor of the RSP is connected in series with a resistor of $R = 1\, \text{k}\Omega$ to a voltage divider (Figure 13). At the selected test frequency of $f = 40\, \text{kHz}$, the values of the impedances of the resistor and the sensor are in the same range. The

| Stress ratio $R_o$ | Frequency $f_o$ | 0.1 | 10Hz |
|--------------------|----------------|-----|-----|
| Maximum stress $\sigma_{max}$ | | 90MPa | |
| Minimum stress $\sigma_{min}$ | | 9MPa | |
| Mean stress $\sigma_m$ | | 49.5MPa | |
voltages at the resistor and at the sensor are measured with the multifunction I/O device NI USB-6251 BNC from National Instruments Corp., Austin, Texas and stored on a computer using a LabVIEW programme. The AC voltage with an amplitude of $U_A = 1\, \text{V}$ is provided by a AFG 3022B frequency generator from Tektronix, Inc., Beaverton, Oregon. All wire connections are soldered.

Starting from approximately 10 s before the start of the fatigue test, the LabVIEW programme stores the ECS data. It continuously performs a measurement every second, reading the voltages of the inputs with a sampling rate of 500 kHz over a period of 40 ms. This corresponds to 20,000 scanning points. From the scanning points, the peak-to-peak amplitudes and phases are calculated and stored in an array with a time stamp.

5.3 | Results and discussion

5.3.1 | Repair effectiveness

The fatigue life $N_{\text{max}}$, defined as the number of load cycles until break, is shown for each of the test groups in a box plot in Figure 14. The box shows the scattering of the middle 50\% of the measured values with an additional marking of the median. The highest and lowest lifetimes are shown by whiskers. The shape of both box plots is typical for fatigue tests. The failure rate increases rapidly, but some very resistant specimens last much longer.

In relative terms, the lowest, the highest and the median values of $N_{\text{max}}$ of the test group with RSP exceed their corresponding values of the test group without RSP by roughly 45\%. A statistical examination, with an assumption of log-normal distributions, shows a highly significant fatigue life-prolonging effect of the RSP. Thus, the repair effect is proven.

![Diagram of circuitry](image13)

**FIGURE 13** Circuitry to record the measured quantities

![Box plots](image14)

**FIGURE 14** Box plots of the maximum number of load cycles $N_{\text{max}}$ endured by the specimens. The box contains the middle half of the values. The whiskers extend to the peak and minimum values of each group
5.3.2 Crack detection effectiveness

Two typical signal curves of ECS during the fatigue tests are shown in Figures 15 and 16. The peak-to-peak voltages from ECS and resistor (cf. Figure 13) are plotted over fatigue test time. In terms of signal quality, the signal curves of 11 ECSs can be divided into two groups with regard to the quality and reliability of crack detection. Six of them work faultlessly; they deliver a continuously increasing signal on which the crack growth can be easily followed (Figure 15). The other group of five ECS delivers a signal that shows crack growth in the overall picture but deviates considerably at individual points in time (see Figure 16). A signal ECS was classified as total failure due to a break at a soldering joint. At this point, it should be mentioned that the sequences of automatic interruption do not show any significant influence on the signal curves. Therefore, the ECS works largely independent of the load.

In Figure 17, the raw signal is plotted over the number of load cycles. In addition, the crack length measured by thermography is plotted; the inner and outer diameters of the coil are shown with dashed lines. At the beginning of the test, both voltages have almost the same value. With increasing crack length, the eddy currents in the aluminium sample are more strongly impeded; the inductance of the coil increases and thus its impedance. Consequently, the voltage $U_{ECS}$ measured at the ECS increases, and $U_R$ decreases accordingly. The first point in time from which a crack is detected by the signal is at a crack length of approximately 16mm, which corresponds to two thirds of the coil width. The point of unequivocal detection of the crack is around 20mm. From this point on, the crack is larger than the outer diameter of the coil. Even beyond that, the signal continues to grow as the crack length increases. The late, very strong increase during the approximately last 1000 load cycles can also be explained. The crack in the aluminium has a considerable width of several millimetres at this point in time; the signal of the coil is almost identical to the signal at pure air. At the end of the experiment, the destruction of the sample is accompanied by the destruction of the ECS.

Although the relation of signal curves and crack length is obvious with a graphical look at the plot, the absolute values vary between different patches, because, for instance, there are slight differences in the thickness of the adhesive.
A different quantity has to be found that permits an objective estimation of the current crack length. In this case, the dimensionless quantity

\[
\Psi = \frac{(U_{ECS} - U_R) - (U_{ECS} - U_R)_{t=0}}{U_{ECS} + U_R}
\]

has a good interrelation with the crack length. Figure 18 reveals that there is also an essential correlation of the dimensionless quantity \(\Psi\) and the relative fatigue life of a specimen. The plot illustrates that the curves of \(\Psi\) are very similar for all faultless ECS, independent of the individual stiffener patch or the varying fatigue life \(N_{max}\).

To fulfill the purpose of a sensor-based stiffener patch, a cancellation criterion has to be defined, for when to replace a structural part, before uncontrolled crack growth starts. For the specific case described here, a criterion of \(\Psi_{crit} = 2\%\) is chosen. When this threshold is exceeded, the crack has roughly the size of the outer ECS diameter, and the estimated remaining lifetime of about 30–40% provides sufficient security.

### 5.3.3 Further investigations

The usability of the above described cancellation criterion is assessed in a further test series that is more lifelike in the light of aircraft maintenance. The voltages of an ECS are not recorded continuously but checked after discrete load cycle intervals. To take into account the fact that aircraft structures are usually checked on ground (under different loading conditions), the specimens are unclamped before each measurement of the ECS. The first load cycle interval comprises 10,000 load cycles, every following interval 2500 load cycles. After each interval, the cancellation criterion of \(\Psi_{crit} = 2\%\) is checked, and if the threshold is exceeded, the test is cancelled. Three specimens are tested in this series. The test results show that the cancellation criterion is reached in every test, before the specimen breaks. Moreover, an investigation of the crack length under a microscope shows that the crack lengths after cancellation are within a range of 1mm for all three specimens (see Table 4).

### 5.3.4 Discussion

The fatigue tests contribute a number of insights into the capabilities of the previously developed patches. Firstly, the RSP were able to prolong the lifetime of the aluminium specimens. Secondly, the built-in ECS is able to track...
the crack growth below the stiffener patch. Thirdly, a criterion could be found to assess the crack length even with fluctuating specimen life. This criterion works also at discrete evaluation points, based on more lifelike testing conditions.

Not all RSP delivered faultless results. Since for some RSP, the signal was influenceable by softly touching the ECS, a loose fit of the ECS is assumed to be the main source of error. This defect may be omitted by additionally glueing the ECS on the broad CFRP ring patch. It should be noted that malfunctions were recognisable straightforwardly, and none of the corrupted RSP were a safety risk, in the sense of falsely underestimating the crack damage.

The retrieval of the inductance information of the ECS with a voltage divider is chosen due to its simplicity. An enhancement would be, to include the ECS in a bridge circuit. Bridge circuits are the standard when it comes to modern well-established applications of the eddy current technique. The appropriate circuit should be chosen with respect to the specific use case. Consequently, a new stop criterion has to be found for new combinations of ECS, stiffener patch, bridge circuit and individual application.

The ultrasonically processed CFRP laminate was able to effectively reduce crack growth during the fatigue tests. Given the fact that for this proof-of-concept, a detailed calculation of the interaction between structure and RSP was neglected, there is optimisation potential for the dimensioning of the broad CFRP ring patch. Possible starting points are the use of unidirectional fibres and, as the ultrasonic processing of CFRP is relatively new, an enhancement of the fabrication process itself, for example, by increasing the fibre volume ration.[31] Furthermore, the repair performance of ultrasonically fabricated CFRP in comparison to CFRP from conventional production may be subject to further studies.

In conclusion, the fatigue tests have shown the possibility to meet both requirements, ‘crack reinforcement’ and ‘crack detection’ with one single sensor-based stiffener patch.

**FIGURE 18** Plot of the dimensionless quantity $\Psi$, calculated from the voltages of ECS and resistor, over the relative lifetime of a specimen

**TABLE 4** Tip-to-tip crack lengths after cancellation criterion $\Psi_{\text{crit}} = 2%$

| Completed load cycles $N$ | Crack length $2a$ |
|--------------------------|-------------------|
| 17500                    | 19.6mm            |
| 17500                    | 20.4mm            |
| 15000                    | 19.5mm            |
CONCLUSIONS

A feasibility study for sensor-based stiffener patches for the bonded repair of metallic structures is presented. Using an ECS, the manufacturing by means of ultrasonic fabrication, as well as the performance in fatigue tests of the patches, is described. The patches meet both requirements ‘crack reinforcement’ and ‘crack detection.’ This holds for continuous crack measurement on the test bench, as well as for discrete measurements on unloaded specimen.

For further studies, other manufacturing options and the inclusion of the ECS in a measurement bridge should be considered. For an application in aircraft maintenance, the patch design has to be tailored and tested for the specific problem and certified for repair purposes.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

[1] Bis research paper number 275, UK Aerospace Maintenance, Repair, Overhaul & Logistics Industry Analysis, no. 275, 2016.
[2] A. Preisler. 2020. Efficient damage detection and assessment based on structural damage indicators, Ph.D. Thesis.
[3] F.-G. Yuan, Structural Health Monitoring (SHM) in Aerospace Structures Edited by F.-G. Yuan, Woodhead Publishing 2016.
[4] K.-U. Schröder, A. Preisler, in Handbuch Industrie 4.0: Recht, Technik, Gesellschaft, Springer 2020, 619.
[5] J. Wiedemann, Leichtbau: Elemente und Konstruktion, Springer-Verlag 2007.
[6] C. Boller, F.-K. Chang, Y. Fujino, Encyclopedia of Structural Health Monitoring, Wiley 2009.
[7] A. A. Baker, R. Jones, Bonded Repair of Aircraft Structures Edited by A. A. Baker, R. Jones, 7, Martinus Nijhoff Publishers 1988.
[8] C. D. Alan Baker, Compos.: Part A 2009, 40, 1340.
[9] V. Tanulia, J. Wang, G. M. Pearce, A. Baker, M. David, B. G. Prusty, Int. J. Fatigue 2020, 105664.
[10] W.-L. Wu, X.-G. Wang, Z.-C. Huang, N.-X. Wu, AIP Adv. 2017, 7(12), 125316.
[11] F. Lambinet, Z. Sharif Khodaei, M. H. Aliabadi, in Key Engineering Materials, Trans Tech Publications Ltd, Kapellweg 8, CH-8806 Baech, Switzerland 2016, 135.
[12] F. Lambinet, Z. S. Khodaei, Eng. Res. Express 2020, 2(4), 45032.
[13] A. Maleki, M. Saeedifar, M. A. Najafabadi, D. Zarouchas, Eng. Fract. Mech. 2019, 210, 300.
[14] T. Becker, U. Prechtel, J. Klauke, M. Kluge, J. Sabater, J. Schalk, Monitoring device for repair patches, repair kit, and method for monitoring a repair patch, US Patent 9,038,458, 2015.
[15] G. E. Georgeson, R. H. Bossi, Patch and methods for monitoring a structure including a patch, US Patent 9,239,315, 2016.
[16] G. E. Georgeson, K. H. Griess, R. L. Keller, E. A. Westerman, Structural repair having optical witness and method of monitoring repair performance, US Patent 9,931,827, 2018.
[17] K. H. Griess, G. E. Georgeson, Smart repair patch and associated method, US Patent 7,398,698, 2008.
[18] J.-B. Ihn, F.-K. Chang, Smart Mater. Struct. 2004, 13(3), 609. https://doi.org/10.1088/0964-1726/13/3/020
[19] J.-B. Ihn, F.-K. Chang, Smart Mater. Struct. 2004, 13(3), 621. https://doi.org/10.1088/0964-1726/13/3/021
[20] S. Ahmed, T. Schumacher, E. T. Thostenson, J. McConnell, in Health Monitoring of Structural and Biological Systems 2017, Society of Photo-Optical Instrumentation Engineers (SPIE), Bellingham, WA, USA 2017, 101700J.
[21] J.-B. Ihn, K. Choi, System and method for monitoring structural health of bonded components, US Patent 10,210,740, 2019.
[22] J. K. Kochan Jr, Structural repair and remote monitoring system and method, US Patent 10,458,134, 2019.
[23] A. Kurnyta, A. Leski, K. Dragan, M. Dziendzikowski, Solid State Phenom. 2015, 220, 349. Trans Tech Publ.
[24] A. A. Baker, L. R. F. Rose, R. Jones, Advances in the Bonded Composite Repair of Metallic Aircraft Structure, Elsevier 2003.
[25] R. Jones, A. A. Baker, N. Matthews, V. K. Champagne, Aircraft Sustainment and Repair, Butterworth-Heinemann 2017.
[26] S. Jiao, L. Cheng, X. Li, P. Li, H. Ding, EURASIP J. Wirel. Commun. Netw. 2016, 1. https://doi.org/10.1186/s13638-016-0689-y
[27] D. P. Roach, K. Rackow, W. DeLong, S. Yepez, D. Reedy, S. White, Use of composite materials, health monitoring and self-healing concepts to refurbish our civil and military infrastructure, Sandia National Laboratories, 2007.
[28] G. Tsamasphyros, G. Kanderakis, N. Drivas, I. Prassianakis, Application of the eddy current method and bragg grating optical sensors for the non destructive testing of bonded composite repairs, Ndt for safety, 2007.
[29] Z. P. Marioli-Riga, G. J. Tsamasphyros, G. N. Kanderakis, in Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware IV, Society of Photo-Optical Instrumentation Engineers (SPIE), Bellingham, WA, USA 2000, 156.
[30] A. Gomer. 2019, Ultraschallfertigung von faserverstärkten kunststoffen, Ph.D. Thesis, Universitätsbibliothek der RWTH Aachen.
[31] A. Gomer, W. Zou, N. Grigat, J. Sackmann, W. K. Schomburg, J. Compos. Sci. 2018, 2(3), 56.
[32] S.-S. Yao, F.-L. Jin, K. Y. Rhee, D. Hui, S.-J. Park, Compos. B: Eng. 2018, 142, 241.
[33] A. B. Strong, Fundamentals of composites manufacturing: materials, methods and applications (2nd edition), Society of Manufacturing Engineers, 2008.
[34] B. D. Agarwal, L. J. Broutman, K. Chandrashekhara, Analysis and Performance of Fiber Composites, John Wiley & Sons 2017.
[35] E. Lenz, Ann. Phys. 1834, 107(31), 483.
[36] J. Bauch, R. Rosenkranz, in Physikalische Werkstoffdiagnostik, (Eds: J. Bauch, R. Rosenkranz), Springer Berlin Heidelberg, Berlin, Heidelberg 2017, 98.
[37] J. García-Martín, J. Gómez-Gil, E. Vázquez-Sánchez, Sensors (Basel, Switzerland) 2011, 11(3), 2525.
[38] C. Hellier, Handbook of Nondestructive Evaluation, 3E, Third edition, McGraw-Hill Education, New York, N.Y. 2020.
[39] J. Sackmann, K. Burlage, C. Gerhardy, B. Memering, S. Liao, W. K. Schomburg, Ultrasonics 2015, 56, 189.
[40] DIN 6791:2012-05, Semi-tubular pan head rivets - nominal diameters 1.6 mm to 10 mm, 2015.
[41] U. Martens, K.-U. Schröder, Compos. Struct. 2020a, 240, 111991.
[42] U. Martens, K.-U. Schröder 2020b. Fatigue & Fracture of Engineering Materials & Structures https://doi.org/10.1111/ffe.13388

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