



Article

Self-Healing Efficiency of a Multidirectional CFRP Laminate After Low-Velocity Impact

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Abstract

The widespread use of carbon fiber-reinforced polymers (CFRPs) in unmanned aerial vehicle (UAV) structures increases the importance of understanding low-velocity impact damage, which is often barely visible yet can significantly reduce residual strength and lead to structural failure during service. This study investigates the impact behavior and healing capability of a multidirectional CFRP laminate with a thermally activated self-healing matrix (CompPair HealTech®). Laminates with a thickness of 1.45 mm were subjected to drop-weight impacts at 5 J and 10 J. After impact, specimens were thermally activated at 150 °C for 30 min and re-impacted under identical conditions. Impact response was evaluated from force, energy, and displacement histories, while residual properties were assessed by compression after impact (CAI) testing and X-ray phase-contrast imaging (XPCI). At 5 J, the re-impact response was nearly identical to the initial impact, with a peak force of approximately 2.1 kN, indicating largely reversible damage. At 10 J, the peak force decreased from ~3.0 kN to ~2.6 kN and displacement increased, reflecting incomplete stiffness recovery caused by more severe damage. Nevertheless, residual compressive strength recovered to ~99% and ~91% of the virgin level for the 5 J and 10 J conditions, respectively. The corresponding healing efficiencies were 86% and 49%. X-ray observations revealed a transition from localized matrix cracking and interfacial damage at 5 J to more extensive internal damage at 10 J. The combined analysis of impact response, residual strength, and damage morphology establishes a direct relationship between damage severity and healing efficiency, demonstrating the potential of thermally activated self-healing composites for rapid recovery of lightweight aerospace structures and UAV components.

Keywords: self-healing composites; carbon fiber-reinforced polymer; low-velocity impact; damage mechanisms; compression after impact; residual strength; aerospace composites

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1. Introduction

Carbon fiber-reinforced polymers (CFRPs) are widely used in aerospace, automotive, and other high-performance applications due to their high specific strength and stiffness. However, their relatively low resistance to impact loading remains one of the major limi-

tations restricting the long-term reliability of composite structures [1,2]. Even low-velocity impacts, such as tool drops, maintenance incidents, or foreign object strikes, may introduce internal damage that is often barely visible on the surface but leads to a substantial reduction in residual mechanical properties, particularly compressive strength [2,3]. This issue is especially critical for lightweight aerospace structures and unmanned aerial vehicles (UAVs), where hidden damage may compromise structural integrity while conventional repair procedures remain labor-intensive and difficult to implement under operational conditions [4].

The impact response of laminated composites is governed by a complex interaction of damage mechanisms, including matrix cracking, interfacial decohesion, delamination, and, at higher impact energies, fiber-dominated failure [1,2]. These mechanisms differ not only in their morphology but also in their influence on residual load-carrying capability. In particular, compressive strength measured using the compression-after-impact (CAI) test is highly sensitive to internal damage and is therefore widely used as a key parameter for structural integrity assessment in impact-damaged composite structures [5,6].

Previous studies have demonstrated that laminate thickness significantly influences both impact damage morphology and residual mechanical performance. Caminero et al. [3] reported pronounced differences in delamination development depending on laminate thickness and stacking sequence, whereas Liao et al. [7] showed that increasing laminate thickness improves impact resistance but simultaneously modifies damage propagation mechanisms and energy absorption behavior. Similar observations were reported by Hiremath and Reddy [8], who demonstrated that ply orientation strongly affects impact-induced damage evolution, while Tai [9] showed that repeated low-energy impacts may lead to progressive degradation of residual mechanical properties even when the initial visible damage remains limited. Additional investigations also confirmed the strong influence of laminate thickness and loading conditions on the impact response and residual behavior of composite laminates [10,11]. Despite the large number of studies devoted to low-velocity impact behavior, most previous studies focus on relatively thick laminates (typically 4–6 mm), for which the impact response is governed predominantly by local material damage rather than by global structural deformation [3,7,10]. In contrast, thin-walled CFRP laminates representative of aerospace skins (approximately 1–2 mm thick) exhibit significantly lower bending stiffness and therefore undergo considerable elastic deflection under impact, even when clamped along the specimen perimeter. This structural flexibility affects the impact force history, energy absorption, and damage evolution, making their behavior fundamentally different from that of thicker laminates. Consequently, the applicability of self-healing concepts to such thin-walled CFRP laminates for lightweight aerospace structures remains insufficiently explored.

In recent years, self-healing composite systems have attracted increasing attention as a promising approach for improving damage tolerance and extending the service life of composite structures [12,13]. Various healing concepts have been proposed, including microcapsule-based systems, vascular networks, dynamic covalent matrices, and thermally activated healing approaches [12–14]. Recent studies have demonstrated the applicability of thermally activated reversible bonding concepts for CFRP structures [14–16]. Such systems enable partial recovery of mechanical properties through controlled heating, eliminating the need for complex repair procedures [17]. This capability is especially valuable for lightweight aerospace structures and UAV components, where rapid or field-assisted restoration can improve operational efficiency and extend service life.

Thermally activated self-healing systems have recently attracted considerable attention because they enable the partial restoration of mechanical properties without complex repair procedures [13,17]. In particular, Scazzoli et al. [18] proposed an alternative methodology for evaluating healing efficiency under post-impact flexural loading, while

Hostettler et al. [19] demonstrated a significant extension of fatigue life in healable composite systems subjected to cyclic loading. Several studies have also shown that healing efficiency strongly depends on the dominant damage mechanism. Zhang et al. [14] reported effective recovery for matrix- and interface-dominated damage, whereas Heo and Sodano [17] observed that fiber-dominated failure mechanisms considerably limit the achievable healing performance.

Despite these advances, the relationship between impact-induced damage morphology, healing efficiency, and the subsequent mechanical response remains insufficiently understood. In particular, the behavior of healed composites under repeated impact conditions has received limited attention. While low-velocity impact tests are commonly used to characterize damage initiation, and CAI tests are employed to evaluate residual strength, the ability of healed laminates to withstand subsequent impact events (re-impact behavior) has not yet been systematically investigated [20]. Recent investigations by Wang et al. [20] confirmed that repeated healing after multiple impacts is possible; however, progressive damage accumulation resulted in a gradual reduction in recovery efficiency and changes in failure mechanisms. Nevertheless, the evolution of residual compressive behavior during repeated impact–healing cycles remains insufficiently understood, particularly for thin CFRP laminates.

Advanced X-ray characterization methods have recently become an important tool for investigating impact-induced damage in composite materials. Wang et al. [21] demonstrated the applicability of in situ X-ray computed tomography for monitoring damage evolution in fiber-reinforced composites, while Sexton et al. [22] showed that X-ray scattering techniques enable multi-scale characterization of internal impact-induced defects in CFRP laminates. Furthermore, Subramani et al. [23] demonstrated the capability of dark-field X-ray imaging to reveal internal damage mechanisms, including ply splitting and delamination, in pseudo-ductile composite laminates. Similarly, Varanges et al. [24] used X-ray microstructural characterization to correlate local structural features with the mechanical performance of complex composite geometries, emphasizing the role of microstructural analysis in understanding damage-sensitive regions. Complementary studies [25–28] have further demonstrated the effectiveness of XPCI, directional dark-field imaging for detecting barely visible impact damage, matrix cracking, fibre breakage, porosity, and delamination in composite structures. These techniques provide enhanced sensitivity compared with conventional radiography and offer valuable information that complements ultrasonic inspection methods, enabling a more comprehensive assessment of damage morphology and extent in fibre-reinforced composites.

Another important aspect is the use of thin self-healing laminates for lightweight aerospace applications. Previous investigations of UAV composite structures with laminate thicknesses of around 5 mm identified critical impact-induced damage at energies close to 15 J [5]. Considering the significantly smaller thickness of the laminates investigated in the present study (1.45 mm), the selected impact energies of 5 and 10 J may therefore be regarded as representative of severe loading conditions for thin-walled lightweight aerospace structures.

The present study addresses these issues by investigating the impact response, damage evolution, re-impact behavior, and residual compressive strength of a multidirectional CFRP laminate with a thermally activated self-healing matrix (CompPair Heal-Tech®). Laminates with a thickness of 1.45 mm were subjected to low-velocity impact at two energy levels, followed by thermal activation, scattering-mode X-ray imaging, and CAI testing. Scattering-mode X-ray imaging was employed as a complementary non-destructive technique to qualitatively visualize internal damage that could not be identified by visual inspection, whereas the primary evaluation of healing efficiency was based primarily on the low-velocity impact and CAI test results. The impact response was analyzed

for the initial impact and the re-impact after healing, whereas residual mechanical performance was evaluated on specimens tested after the initial impact and after healing, respectively.

The main objective of this work is to establish a direct relationship between the nature of impact-induced damage and the effectiveness of healing in thin self-healing CFRP laminates. The novelty of the study lies in the combined analysis of impact response, re-impact behavior, and residual compressive performance, supported by X-ray observations of internal damage evolution. The obtained results provide new insights into damage–healing interactions and demonstrate the potential of thermally activated self-healing composites for improving durability and enabling rapid repair of lightweight structures, including UAV components.

2. Materials and Methods

A multidirectional CFRP laminate was manufactured from a unidirectional carbon fiber-reinforced polymer prepreg with a thermally activated self-healing matrix (CompPair HealTech® T700-UD200-36RW-300; CompPair Technologies Ltd., Renens, Switzerland). This material system was selected due to its ability to partially restore mechanical properties after thermal activation, which makes it particularly attractive for lightweight aerospace structures subjected to accidental impact loading and operational damage [13,17,18].

The laminates were manufactured using a vacuum bagging process and cured in a laboratory oven in accordance with the material processing guidelines, representing a fabrication route commonly used for lightweight aerospace composite structures. The layup configuration was a balanced and quasi-symmetric laminate [0/+45/90/−45/−45/90/+45/0], resulting in a final thickness of 1.45 ± 0.02 mm. The main material and processing parameters are summarized in Table 1. Such a relatively small laminate thickness was intentionally selected to investigate the applicability of self-healing concepts to thin-walled composite structures representative of UAV components and lightweight aerospace applications.

Table 1. Material system, laminate configuration, and processing parameters of the investigated CFRP laminates.

Parameter	Value
Material	CompPair HealTech®
Layup	[0/+45/90/−45/−45/90/+45/0]
Thickness	1.45 ± 0.02 mm
Cure temperature	145 °C
Post-cure temperature	185 °C
Healing temperature	150 °C
Healing duration	30 min

The CompPair prepreg was cured at 145 °C for 210 min, followed by post-curing at 185 °C for 150 min, with a heating rate of 2 °C/min. After curing, the laminate plates were cut into specimens measuring 150 mm × 100 mm in accordance with ASTM D7136/D7136M and ASTM D7137/D7137M [6,29] (Figure 1).

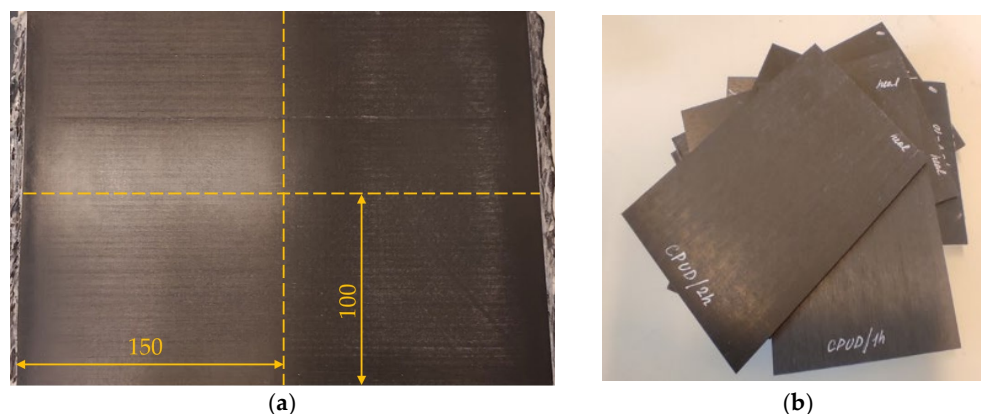


Figure 1. Geometry and representative specimens of the investigated CFRP laminates (CompPair HealTech®, thickness 1.45 mm): (a) Cured laminate plate before specimen preparation; (b) Representative specimens prepared for impact and CAI testing.

Low-velocity impact tests were performed using a drop-weight impact tower (Rosand IFW8; Rosand Precision Ltd., Stourbridge, UK) equipped with a hemispherical impactor with a diameter of 40 mm and a mass of 5.344 kg. The nominal impact energies of 5 J and 10 J were achieved using drop heights of 0.131 m and 0.252 m, respectively, taking into account the friction losses specified for the impact tower. All tests were conducted under controlled environmental conditions (21 °C and 44% relative humidity). Impact energies of 5 J and 10 J were selected to induce barely visible impact damage (BVID) without complete penetration of the laminate, which is characteristic of operational impact scenarios in lightweight composite structures [3,7]. During testing, force–time, absorbed energy–time, and displacement–time responses were continuously recorded.

To evaluate the effect of healing on impact response, a subset of specimens was subjected to thermal activation after the initial impact event. Healing was performed in an oven at 150 °C for 30 min in accordance with the material specifications and previously reported thermally activated healing approaches [3,18]. After healing, the specimens were re-impacted under identical conditions in order to evaluate the recovery of impact response and the ability of the material to sustain repeated loading.

Residual mechanical properties were evaluated using compression after impact (CAI) testing in accordance with ASTM D7137/D7137M [6] on a Schenck Trebel RME 600 (SCHENCK RoTec GmbH, Darmstadt, Germany) testing machine (Figure 2).



Figure 2. Experimental setup for compression after impact testing, showing the anti-buckling fixture and specimen positioning in the testing machine.

For each experimental condition, five specimens were tested ($n = 5$) (Table 2, Figure 3). The reported results correspond to the average values obtained from repeated experiments, while the associated standard deviation values were used for statistical evaluation. Separate specimen sets were prepared for the impact and compression-after-impact investigations (Figure 3). For the CAI tests, the specimen groups were designated as follows: CPUDV (unimpacted reference), CPUD1 (5 J impact), CPUD2 (10 J impact), CPUD1h (5 J impact followed by thermal healing), and CPUD2h (10 J impact followed by thermal healing). The healed groups underwent thermal healing after impact and were subsequently tested in compression to evaluate the healing efficiency. The second part of the samples, CPUD1h and CPUD2h, was subjected to a second impact to estimate the recovery. Anti-buckling fixtures were used to prevent global instability during compression loading. The residual compressive strength was calculated based on the maximum load prior to failure and the cross-sectional area of the specimens.

Table 2. Experimental program and specimen sets used in the study.

Specimen Set	Impact Loading, J	Healing
CPUDV	0	-
CPUD1	5	-
CPUD2	10	-
CPUD1h	5	healing
CPUD2h	10	healing

Internal damage was characterized using grating-based X-ray phase-contrast imaging (XPCI). This technique enables measurement of 3 types of images corresponding to different physical mechanisms and specimen properties. Absorption images quantify X-ray absorption via Compton scattering and the photoelectric effect. Refraction images show the phase shift of X-rays caused by variations in the specimen's refractive index. Scattering (dark-field) images measure the reduction in interference visibility due to ultra-small-angle X-ray scattering caused by microscopic defects and inhomogeneities in the specimen. Among the available imaging modes (absorption, refraction, and scattering), scattering images were selected due to their higher sensitivity to internal defects and interlaminar damage [23,24]. The analysis focused on identifying matrix cracking, interfacial decohesion, and delamination in impacted and healed specimens.

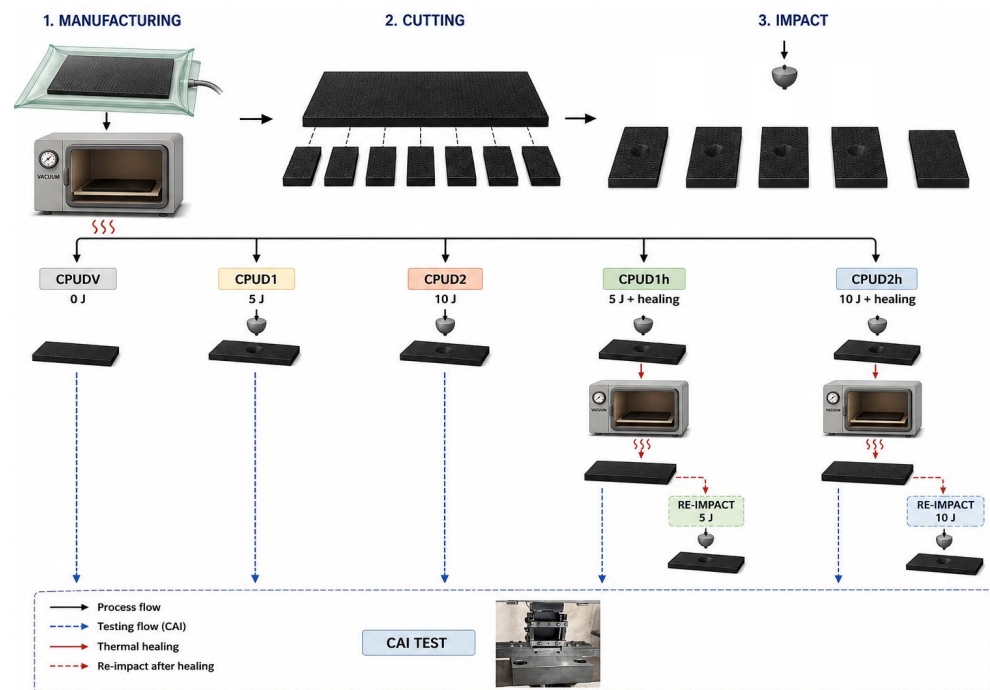


Figure 3. Schematic illustration of the experimental workflow for impact and CAI investigations.

To enable a quantitative comparison of residual mechanical performance and healing efficiency, the residual compressive strength was normalized with respect to the virgin laminate state [18,30]:

$$R_{\sigma} = \frac{\sigma_{CAI}}{\sigma_{virgin}} \times 100\%, \quad (1)$$

where σ_{CAI} is the compressive strength after impact and σ_{virgin} is the compressive strength of the undamaged specimen.

The healing efficiency was calculated as

$$\eta_h = \frac{\sigma_{CAI,healed} - \sigma_{CAI}}{\sigma_{virgin} - \sigma_{CAI}} \times 100\%, \quad (2)$$

where $\sigma_{CAI,healed}$ is the compressive strength of the healed specimen.

The damage index was defined as

$$D = \left(1 - \frac{\sigma_{CAI}}{\sigma_{virgin}} \right) \times 100\%. \quad (3)$$

These parameters enable a quantitative assessment of the relationship between damage severity, residual compressive performance, and healing efficiency.

3. Results and Discussion

3.1. Impact Response and Energy Dissipation

The impact response of the investigated self-healing CFRP laminates was analyzed using force–time, absorbed energy–time, and displacement–time curves obtained during drop-weight testing at impact energies of 5 J and 10 J (Figure 4 and Table 3). Figure 4 presents representative curves characteristic of each specimen series, whereas the corresponding impact parameters listed in Table 3 are reported as mean values obtained from the specimens set.

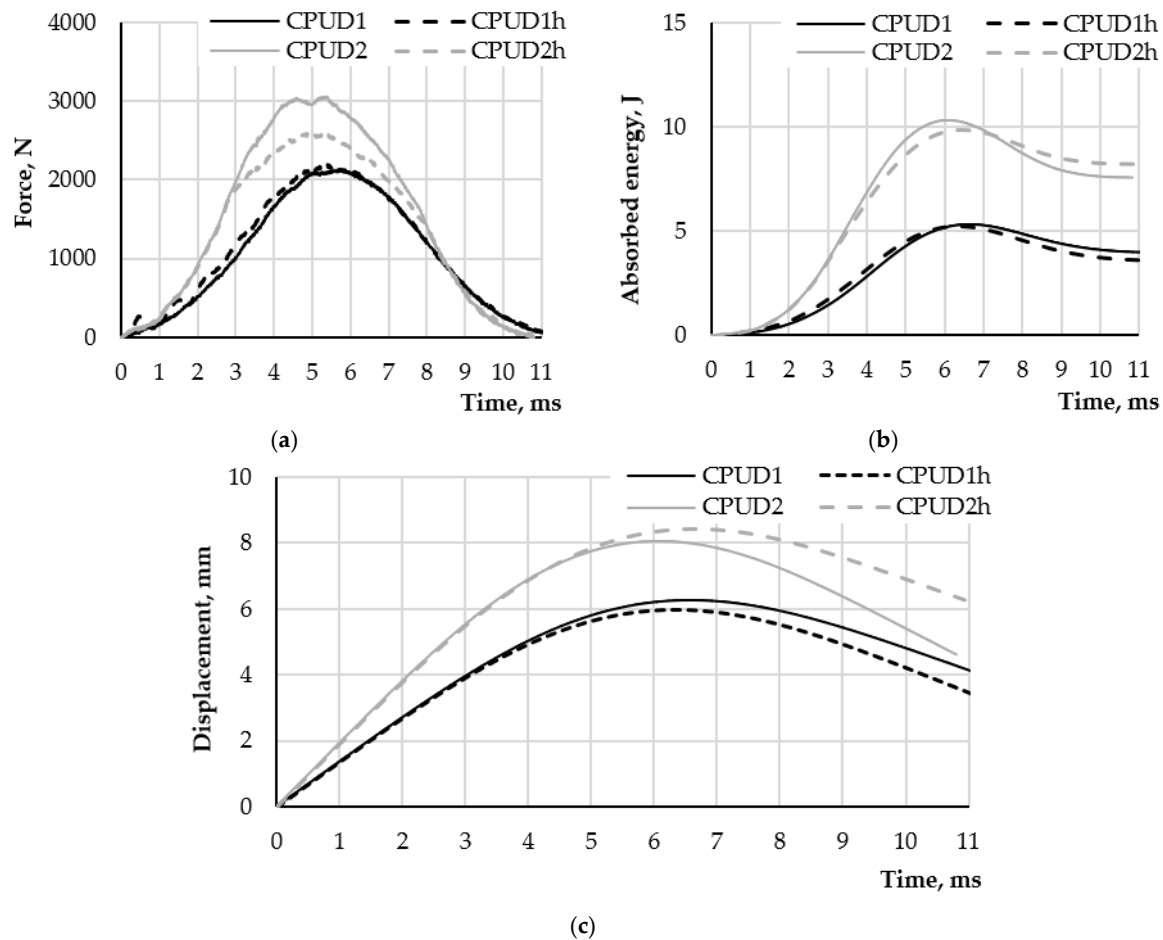


Figure 4. Impact response of self-healing CFRP laminates: (a) force–time; (b) absorbed energy–time; (c) displacement–time curves for impact energies of 5 J (CPUD1 and CPUD1h) and 10 J (CPUD2 and CPUD2h) before and after healing.

The force–time curves (Figure 4a) exhibit a typical response of laminated composites under low-velocity impact, consisting of an initial elastic contact phase followed by progressive damage development. Comparable behavior has been widely reported for CFRP laminates under similar loading conditions [1–3]. The initial stage is governed primarily by local contact stiffness, while the subsequent nonlinear response is associated with the initiation and evolution of damage mechanisms such as matrix cracking and delamination.

Table 3. Average maximum force, absorbed energy and displacement corresponding to statistical parameters after impact.

Specimen	Maximum Force			Maximum Absorbed Energy			Maximum Displacement		
	Value, N	Std, N	CV, %	Value, J	Std, J	CV, %	Value, mm	Std, mm	CV, %
CPUD1	2133	138	6.5	5.29	0.003	0.1	6.25	0.067	1.1
CPUD1h	2183	64	2.9	5.24	0.086	1.6	5.96	0.438	7.3
CPUD2	3053	41	1.4	10.35	0.015	0.1	8.04	0.079	1.0
CPUD2h	2583	141	5.5	9.88	0.321	3.2	8.44	0.155	1.8

Std—standard deviation; CV—coefficient of variation.

At 5 J impact energy, the peak force remains nearly unchanged (≈ 2.1 kN) for both impacted and healed specimens (Table 3). In contrast, at 10 J, a 15.4% reduction in peak force after healing was observed, suggesting that stiffness degradation induced by higher-

energy impact is not fully recovered through thermal activation. Similar incomplete recovery has been reported for thermally healable CFRP systems under cyclic loading [17], and is commonly attributed to persistent matrix, interfacial and, at higher damage levels, fiber-related defects.

Displacement–time curves (Figure 4c) provide further insight into the structural response. At 5 J, the healed specimens exhibited 4.6% reduction in maximum displacement (0.29 mm), indicating reduced structural compliance after thermal activation. However, at 10 J, the healed specimens show a higher maximum displacement (8.44 mm) than the impacted CPUD2 specimens (8.04 mm, Table 3), reflecting incomplete recovery of the internal damage state and increased structural compliance due to residual damage.

Additional information is provided by the force–displacement curves (Figure 5). At 5 J, the initial impact and re-impact curves are nearly identical in slope and maximum displacement, indicating effective recovery of the mechanical response after healing. In contrast, at 10 J, the re-impact specimen reaches a larger maximum displacement and a lower peak load than the corresponding impacted specimen, indicating incomplete recovery of the mechanical response after healing. Despite these differences, the absorbed impact energy, represented by the area under the force–displacement curve, remains comparable between the initial impact and the re-impact after healing at both energy levels. This suggests that thermal healing does not significantly affect the overall energy absorption capacity.

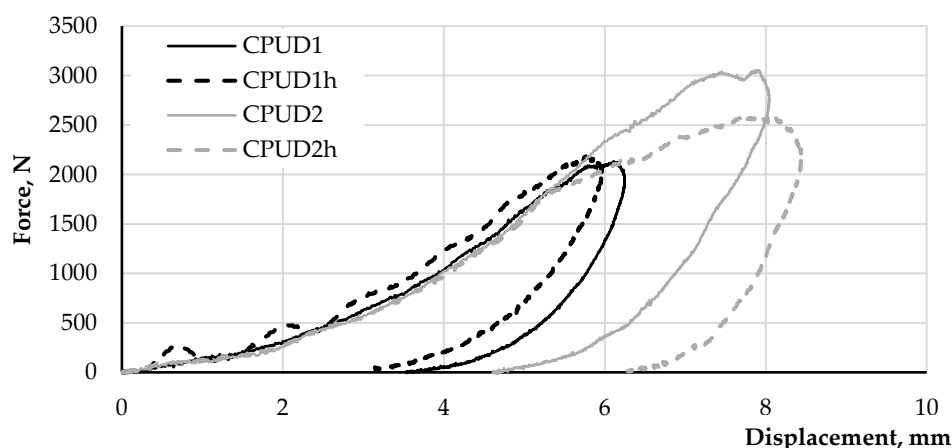


Figure 5. Force–displacement curves of self-healing CFRP laminates subjected to low-velocity impact at 5 J (CPUD1 and CPUD1h) and 10 J (CPUD2 and CPUD2h) during the initial impact and re-impact after thermal healing.

Overall, the force–time, displacement–time, and force–displacement responses indicate that the global impact behavior is largely preserved after thermal healing. However, the reduction in the peak force, together with the increase in maximum and rebound displacements observed after higher-energy impact, indicates mechanical response due to residual internal damage. These findings are consistent with the X-ray observations presented in Section 3.2, which reveal that damage associated with higher impact energies is only partially restored during thermal healing. The pronounced sensitivity of the investigated 1.45 mm laminates to impact loading further highlights the importance of damage-tolerant and self-healing concepts for thin-walled lightweight aerospace structures and UAV applications.

3.2. X-Ray Analysis of Damage Evolution and Healing Efficiency

To qualitatively evaluate the evolution of internal damage after impact loading and subsequent thermal recovery, X-ray examination was performed using scattering-mode imaging [21–24]. Representative optical photographs and X-ray images of the specimens after impact and after healing for impact energies of 5 J and 10 J are presented in Figures 6 and 7, respectively. In the virgin state, the laminate exhibits a relatively uniform scattering pattern without pronounced localized defect regions, indicating the absence of pronounced scattering features associated with internal defects within the sensitivity of the method.

The X-ray observations presented in this section provide a qualitative assessment of damage morphology together with the mechanical test results and the relevant literature and are not intended for the direct quantitative characterization of individual damage mechanisms.

After impact at 5 J, the optical photograph (Figure 6a) reveals only a slightly darker spot at the impact location, with no visible signs of surface damage or delamination. In contrast, the X-ray image (Figure 6b) of CPUD1 shows localized bright lines, although the overall damage contrast remains relatively low. These features may be associated with matrix-dominated damage, interlaminar defects, and local degradation of the fiber–matrix interfacial bonding. After thermal healing, the X-ray scattering pattern of the specimens (CPUD1h) becomes visually closer to that of the virgin material (Figure 6c), suggesting a qualitative reduction in the extent of the observed damage features in the matrix-related damaged regions. These observations are consistent with the mechanical test results, which showed a nearly complete recovery of the residual compressive strength after healing for the 5 J impact condition.

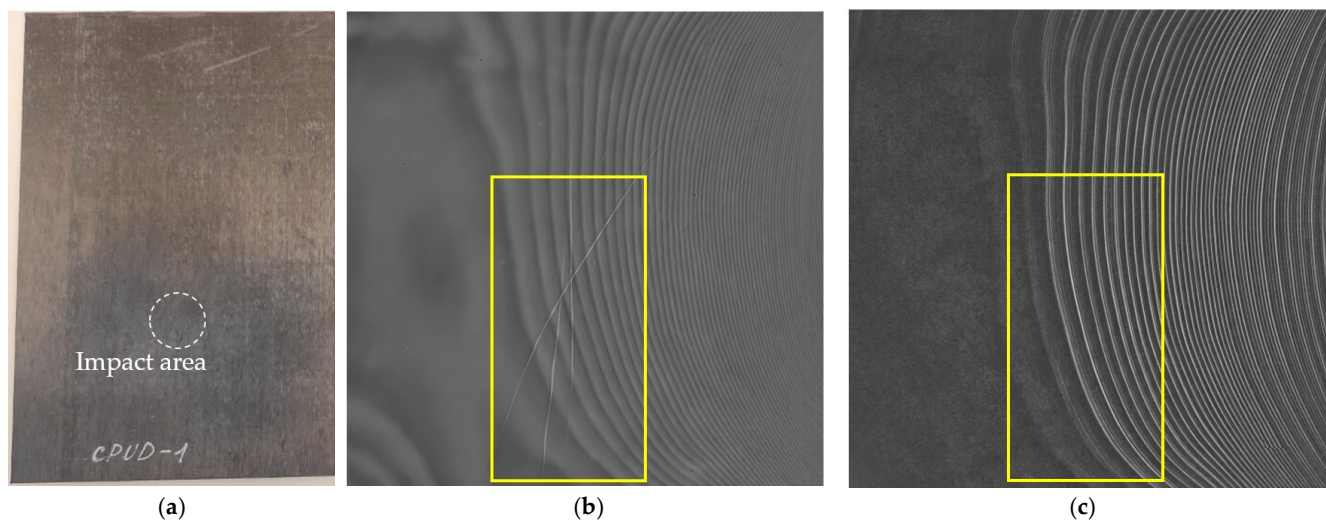


Figure 6. Optical photograph (a) and scattering-mode X-ray images of CFRP laminates subjected to 5 J impact: (b) a specimen (CPUD1) after impact; (c) a specimen (CPUD1h) after thermal healing.

The X-ray images qualitatively indicate a more extensive damaged region after impact at 10 J (Figure 7). Although the optical photograph (Figure 7a) of CPUD2 shows only a larger darkened impact area without any visible signs of surface cracking or delamination, the X-ray scattering image reveals a visually larger damaged region (Figure 7b), accompanied by a higher density of scattering features (bright lines) and a more complex defect morphology. Compared to the 5 J condition, the damage in CPUD2 is considerably more extensive. It is likely associated not only with matrix cracking and interlaminar defects but also with damage extending beyond the matrix-dominated mechanisms observed at 5 J impact. After thermal healing of the 10 J specimens (CPUD2h), the intensity

of the damage-related scattering features decreases (Figure 7c). However, the damage morphology remains more pronounced than in specimens impacted at 5 J and healing, suggesting incomplete structural recovery after higher-energy impact loading. These observations are consistent with the mechanical test results of CPUD2h, which showed only partial recovery of the residual compressive strength after healing. The correlation between the remaining internal damage and the reduced mechanical recovery agrees well with previously reported limitations of thermally activated healing systems when fiber-dominated damage mechanisms are involved [17,18].

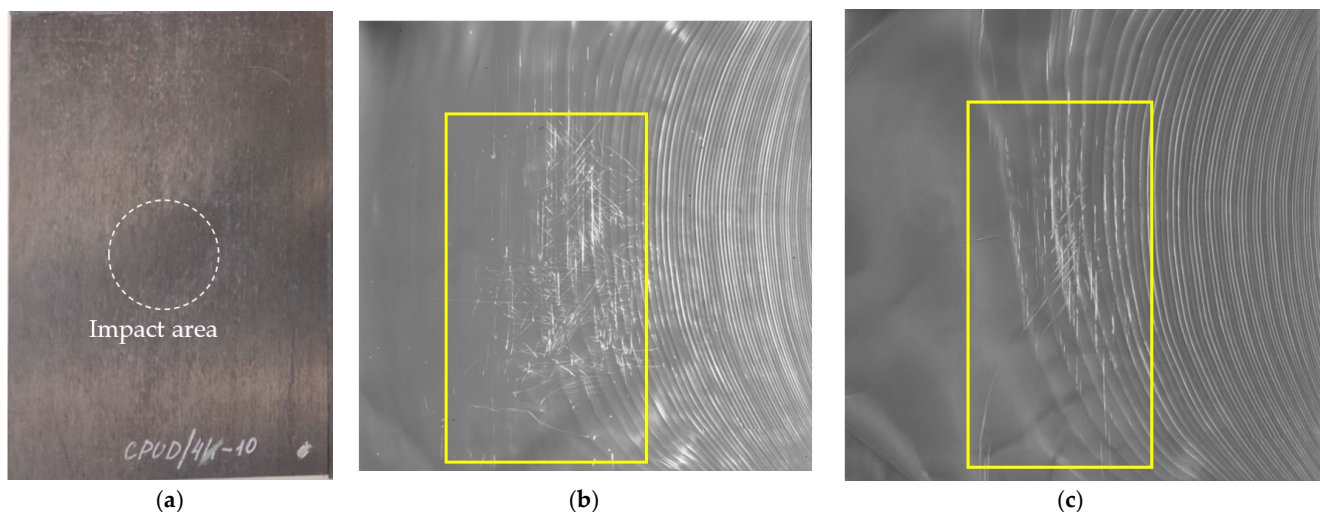


Figure 7. Optical photograph (a) and scattering-mode X-ray images of CFRP laminates subjected to 10 J impact: (b) a specimen (CPUD2) after impact; (c) a specimen (CPUD2h) after thermal healing.

These qualitative X-ray observations complement the mechanical test results and should not be interpreted as a quantitative measure of damage severity. The combined X-ray observations and mechanical test results suggest that the healing efficiency depends on the dominant damage mechanisms induced by impact loading. The results suggest that thermally activated healing is more effective for damage primarily associated with matrix-related mechanisms than for damage involving more extensive structural disruption. These observations suggest that the degree of mechanical recovery is strongly influenced by the extent of irreversible damage to the reinforcing structure.

3.3. Compression After Impact Response and Residual Strength Recovery

Low-velocity impact loading is one of the most critical damage scenarios for thin composite structures, since even relatively low impact energies may generate internal defects that significantly reduce the residual mechanical performance without producing severe visible surface damage. Similar reductions in residual compressive strength after impact loading have previously been reported for thin CFRP laminates subjected to impact-induced delamination damage [2,4]. Therefore, compression after impact testing was carried out to evaluate the influence of impact loading and the effectiveness of the thermal healing procedure on the residual compressive behavior of the self-healing CFRP laminates with a thickness of 1.45 mm.

The obtained load–displacement curves from the CAI test are presented in Figure 8. The experimental results clearly demonstrate the influence of impact energy on the stiffness, maximum load, and post-peak response of the investigated composite laminates.

The virgin specimens exhibited a nearly linear increase in load up to the maximum force level of 27 kN, followed by a sudden load drop without catastrophic failure (Figure 8) as the load subsequently began to increase again. Such post-peak behavior is typical for

thin composite laminates subjected to compressive loading and is associated with the progressive development of interlaminar damage and edge crushing of the specimen. All observed compressive residual-strength failure modes in virgin samples were classified as CAB (end Crushing (failure type)-At end/edge (failure area)-Bottom (failure location)) per ASTM D7137.

After impact at 5 J, CPUD1 exhibited a lower peak load of 26.5 kN and an earlier deviation from the linear response (Figure 8) at 1 mm in comparison with 1.1 mm for CPUDV, indicating that the impact-induced defects reduced the compressive stiffness and accelerated the onset of local instability. However, post-impact damage remained relatively localized under compression, and failure also occurred at the ends of the specimen and was classified as CAB according to ASTM D7137. Following thermal healing of CPUD1h, the peak load increased, approaching the virgin sample's peak load of 27 kN. This is in good agreement with the recovery observed by the X-ray examination (Figure 6c).

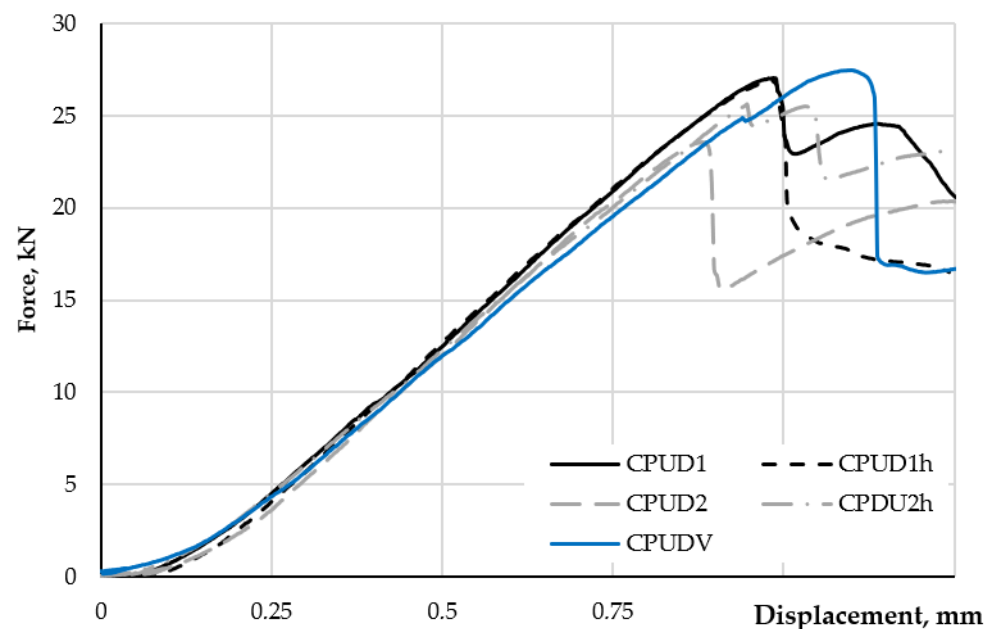


Figure 8. Representative load–displacement curves obtained during compression–after–impact testing of CFRP laminates: virgin (CPUDV); impacted (5 J) (CPUD1), and healed specimens after impact at 5 J (CPUD1h); impacted (10 J) (CPUD2) and healed specimens after impact at 10 J (CPUD2h) laminates.

In contrast, the specimens CPUD2 impacted at 10 J exhibited a reduced peak load of 24 kN and an earlier loss of stability at 0.87 mm (Figure 8). The force–displacement curves from the CAI tests showed reduced stiffness, an earlier onset of instability, and pronounced load drops after reaching the maximum force level. In three of the five specimens, progressive delamination developed and the failure mode was classified as SGM (Splitting (failure type)—Gage, away from damage (failure area)—Middle (failure location)) destruction; in the remaining two, there was crushing at the ends—CAB in accordance with ASTM D7137. After thermal healing of the 10 J specimens, only partial recovery of the mechanical properties was observed (Figure 8). The maximum load increased after healing by 10%, but did not reach the initial values of the undamaged virgin specimen. After healing, post-impact damage was localized under compression, and failure occurred at the ends of the specimen and was classified as CAB according to ASTM D7137. This suggests that, at higher impact energies, the self-healing mechanism cannot fully restore

the impact-induced damage. The observed dependence of healing efficiency on damage severity agrees well with previously reported behavior of thermally activated self-healing composite systems [17,18,30].

The summarized CAI test results are presented in Table 4. For the specimens impacted at 5 J, the residual compressive strength reached 173.11 MPa, corresponding to 89% of the virgin level. After thermal healing, this value increased to 190.74 MPa, or 99% of the initial strength level. In addition, the healing efficiency parameter η_h (2) reached 86%, while the damage index D (3) decreased from 11% to 2%, indicating substantial recovery of the load-carrying capability after healing.

Table 4. Average residual compressive strength values and corresponding statistical parameters obtained from repeated CAI tests ($n = 5$) of CFRP laminates after impact and thermal healing.

Specimen	Residual Compressive Strength, MPa	Std, MPa	CV, %	R_σ , %	η_h , %	D, %
CPUDV	193.63	5.00	2.6	100	–	0
CPUD1	173.11	11.23	6.5	89	–	11
CPUD1h	190.74	5.59	2.9	99	86	2
CPUD2	159.41	5.09	3.2	82	–	18
CPUD2h	176.27	7.64	4.3	91	49	9

Std—standard deviation; CV—coefficient of variation; R_σ —normalized residual compressive strength; η_h —healing efficiency; D—damage index.

For the 10 J impact condition, the residual compressive strength decreased to 159.41 MPa, corresponding to 82% of the virgin level. After healing, the residual strength increased to 176.27 MPa (91% of the virgin level), whereas the healing efficiency η_h reached 49%. The damage index after healing remained at the level of 9%, confirming the incomplete restoration of the laminate structure after more severe impact loading.

For a clearer comparison of the residual compressive strength after impact and thermal healing, the corresponding bar chart with standard deviation values is presented in Figure 9. The statistical comparison further confirms the strong dependence of healing efficiency on impact severity. The obtained results are in good agreement with both the CAI curve analysis and the X-ray observations. In the case of 5 J impact loading, a substantial recovery of the mechanical properties was observed, whereas the recovery after 10 J impact remained only partial.

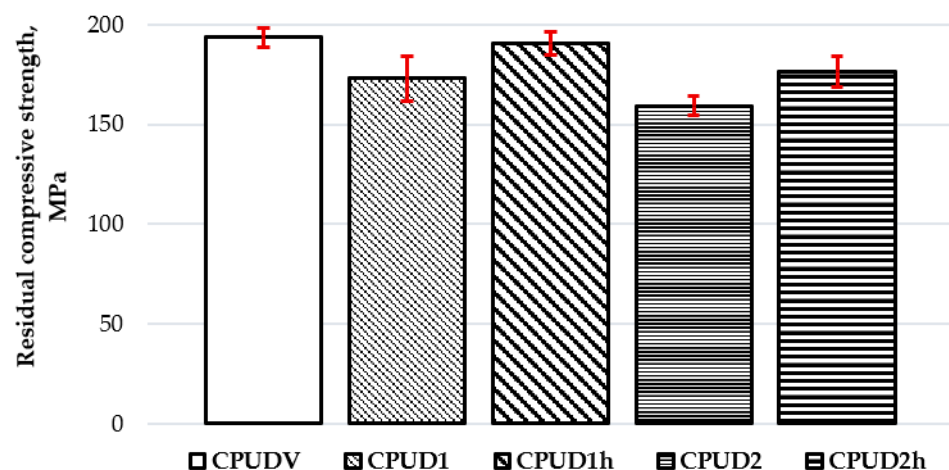


Figure 9. Residual compressive strength of CFRP laminates after impact and healing under different loading conditions. Error bars represent the standard deviation.

Moreover, the relatively low coefficient of variation values (2.6–6.5%) indicate good repeatability of the obtained experimental results and sufficient stability of the mechanical response of the investigated laminates.

The obtained results demonstrate that the self-healing efficiency of the CFRP laminates strongly depends not only on the impact energy level but also on the nature of the generated internal damage. In the case of 5 J impact loading, the damage was mainly dominated by localized matrix and interlaminar defects, which could be effectively partially restored during thermal healing, resulting in a substantial recovery of the residual compressive strength. In contrast, the 10 J impact condition produced a more complex damage structure involving developed delamination regions and local disruption of the reinforcing structure, which significantly limited the recovery capability of the mechanical properties.

From a practical point of view, the obtained results indicate the potential applicability of self-healing CFRP laminates in lightweight aerospace and UAV structures subjected to accidental low-velocity impact loading during operation. The demonstrated recovery of residual compressive strength after thermal healing may be particularly relevant for rapid maintenance and temporary restoration procedures under field-service conditions.

4. Conclusions

The obtained results demonstrated that low-velocity impact loading significantly influences the residual mechanical performance of the investigated self-healing CFRP laminates, while the severity of degradation strongly depends on the impact energy level. Scattering-mode X-ray imaging revealed that impact loading at 5 J mainly produced localized matrix-dominated and interlaminar damage, whereas the 10 J impact condition generated a more complex damage structure characterized by larger defect regions and more pronounced internal degradation.

CAI testing showed that the thermal healing procedure substantially improved the residual compressive performance of the impacted laminates. After healing, the residual compressive strength recovered up to 99% of the virgin level for the 5 J condition and up to 91% for the 10 J condition. The calculated healing efficiency reached 86% for the 5 J impact condition, while for the 10 J condition it decreased to 49%, indicating that the recovery capability strongly depends on the severity and complexity of the impact-induced damage.

Analysis of the load–displacement curves demonstrated that the healed specimens subjected to 5 J impact exhibited deformation behavior and post-peak response close to those of the virgin laminates. In contrast, the specimens impacted at 10 J retained signs of structural instability and progressive damage evolution even after thermal healing. The post-test damage morphology observations were in good agreement with both the CAI behavior and the X-ray analysis results.

Overall, the combined analysis of impact response, scattering-mode X-ray imaging, residual compressive behavior, and post-test damage morphology demonstrates that thermally activated self-healing CFRP laminates can effectively restore structural integrity after low-energy impact damage. The high level of residual strength recovery achieved after a single thermal healing cycle highlights the potential of this material system for lightweight aerospace structures, where accidental impact damage may occur during manufacturing, handling, and assembly, as well as throughout service. The ability to recover mechanical performance by a simple thermal treatment, without replacing the component or performing complex repair procedures, offers a promising route toward more damage-tolerant, maintainable, and cost-efficient composite structures with extended service life.

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