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# PROGRESSIVE DAMAGE IN THIN 2D WOVEN CFRP LAMINATES DUE TO STRESS CONCENTRATIONS AT FREE EDGES AND NOTCHES

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**Summary:** *Stress concentrations are present at cut-outs, notches, and generally at free edges in woven CFRP structures. Under cyclic loading, damage initiates from these stress raisers and progresses into the laminate, leading to strength reduction and structural failure.*
*The present contribution provides a literature review summarizing analytical, experimental and numerical investigations regarding damage initiation and propagation in the presence of free edges and at notches in thin plain-woven 2D CFRP laminates. For free edges, initiation of damage is given as interlaminar matrix cracking. Modelling approaches for the progression by cohesive zone models or linear-elastic fracture mechanics are summarized. Recent advances using image correlation and numerical modelling are presented. In terms of notches, a brief survey of relevant literature is given, followed by a more detailed treatment of the damage progression originating from a circular hole. Additionally, the shortcomings of standard specimens with holes for fatigue damage progression investigations are addressed, since both mechanisms, damage from the free edge and the hole, interact. Latest research to uniquely identify the damage emanating from the hole is presented.*

## 1 Introduction

Carbon fiber reinforced polymers (CFRPs) are used increasingly in aeronautical and automotive applications to achieve targets for energy-efficiency in transportation. In particular, the high specific stiffness and strength values, and the weight-saving potential, combined with excellent fatigue response and damage tolerance, has led to widespread component development and manufacturing using CFRPs [1, 2].
When designing components for high-performance applications, safety and operational reliability are of great importance along with component stability and structural integrity [3]. Most engineering designs of thin-walled composite parts follow the classical lamination theory (CLT) where, after pre-selection of a material system (fiber, matrix) and definition of the loads, a laminate stiffness based stress analysis is performed. A subsequent failure analysis in accordance to an appropriate failure criterion and associated

strength parameters of the material system follows and provides necessary information regarding component structural integrity [1, 3].
Regardless of the selected failure criterion or loading condition, the CLT faces several limitations when more complex components are analysed. CLT is based on the assumptions of small deformations, ideally bonded plies, linear ideal-elastic material behavior of the plies, with the laminate representing a homogeneous continuum. In addition, the CLT is valid only inside the laminate, meaning far away from boundaries. If the emphasis is placed on safety and reliability, any manufacturing flaws (e.g. ply folds, voids, dry spots) or design features (e.g. transitions in thickness, cut-outs) have to be addressed, but these are often beyond the application limits of the CLT [4, 5].
These types of geometric changes and manufacturing flaws cause stress concentrations which have a non-negligible effect on the structural integrity and thus also on safety and reliability. Generally, margins of safety are large enough so that small manufacturing flaws, which are not detected by quality control, do not cause failure. In contrast, the stress concentrations caused by engineering design have to be considered in advance [4]. Here, numerical techniques (e.g. finite element method (FEM)) and analytical approaches, supported by experimental preliminary tests are involved.
These stress concentrations occur at numerous locations within the laminate, e.g. due to variations in thickness, notches, at interfaces to other components (e.g. joints, fittings) [6, 7] or also at the edges of the components (free edge).
Two types of stress concentrations and their effect on progressive damage are reviewed in this paper. At the beginning, relevant literature concerning the stress concentration induced by the free edge is reviewed. Subsequently, damage initiation and propagation originating from notches is investigated. The last section contains a conclusion and an outlook on planned research activities at the author's institute.

## 2 Stress concentration at free edges

When plies are arranged in different directions, the free-edge effect appears as interlaminar stress concentration in the vicinity of the laminate margins, between those plies that are arranged in different directions. This is caused by a discontinuous change of the elastic ply material properties and resultant interlaminar stresses [7]. In theory, a local stress singularity exists at the free edge, quickly decreasing towards the center of the laminate (the significant influence is limited to a distance equal to the laminate thickness). Since the material is weaker in thickness direction compared to the in-plane directions, the free-edge effect may jeopardize the load-bearing capacity, as emphasized by Mittelstedt et al.[8].

### 2.1 Stress concentration at free edges under static loading

Fundamental work concerning interlaminar stresses has been done by Pipes and Pagano [9], where the exact elasticity equations were approximated by a finite-difference approach. Doing so, a symmetric angle-ply CFRP laminate was used, revealing a singularity of interlaminar shear stresses [9]. The prominence of this singularity has led to the introduction of a variety of close-form approaches in order to describe the stresses near the free edge, since an unified formulation for general laminates is not possible as a result of the high complexity and the occurring singularity.

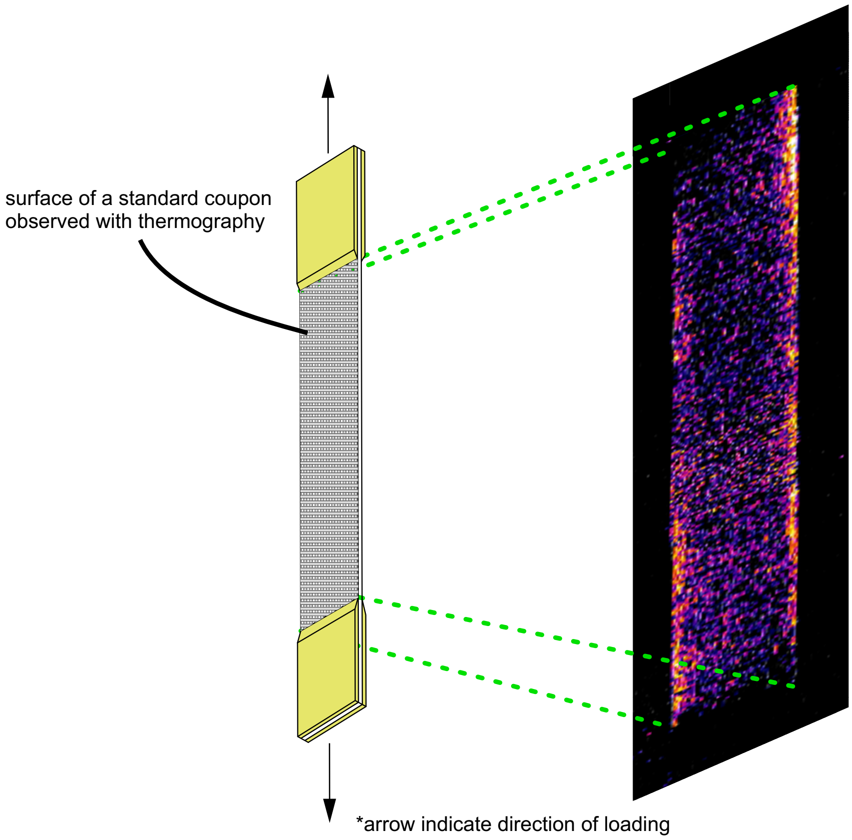


**Figure 1**: Common damage to the free edge following tension-tension fatigue loading of a plain-woven standard coupon observed by thermography.

Attempts were made to use Fourier series to approximate the displacements and to solve with them the elasticity equations [10], or to apply a higher-order plate theory on a ply basis [11], whereby the latter approach includes a warp deformation mode of the free edge. Besides angle-ply laminates, Kassapoglou and Lagace [12] have studied cross-ply laminates. They applied a force balanced method and used the principle of minimum complementary energy to obtain a solution of interlaminar stresses at a straight free edge. Use of the principle of minimum complementary energy was also made by Flanagan [13], who expressed the stress functions in thickness direction by a harmonic series expansion. To the extent that bending and twisting are also present besides extension, the approaches of Yin [14], or the iterative approach of Cho and Kim [15] can be taken. Yin et al.[14] developed an approach based on the stress functions of Lekhnitskii [16], that determines the interlaminar stresses on a ply basis. Cho and Kim [15] extended the approach established by Cho and Yoon [17], based itself on the extended Kantorovich method [18].
Besides these close-form approaches, numerical methods provide a convenient way to evaluate the stresses in the vicinity of the free edge. As shown by Whitcomb et al. [19], stresses computed by FEM provide excellent agreement to those obtained by analytical approaches, conscious that the stresses in the element closest to the singularity do not agree. Reducing the size of the elements leads to better results, but at the expense of

computation time. In order to compensate this, Lessard [20] introduced a ”sliced-model”, which can be interpreted as a kind of submodel. This ”sliced-model” allows to reduce size of the elements significantly while maintaining a reasonable computation time. Furthermore, Carrera et al. [21] developed a numerical model based on a high-order beam theory, with which the stress field at free edges in generic laminated composites can be described. Apart from three-dimensional FEM, investigations were carried out to determine whether two-dimensional approaches are appropriate [22, 23, 24].

The investigations quoted in advance were concerned with unidirectional angle-ply and cross-ply laminates. For woven laminates, only a small body of scientific literature exists. Again analytical approaches to describe interlaminar stresses were developed [25, 26]. Besides initial numerical investigations of the free-edge effect in plain weave laminates were carried out by Whitcomb et al.[27]. Their FEM models based on repetitive volume elements (RVE) reveal different stress distributions and levels than comparable UD laminates. Besides, a clear dependence on the weave architecture was found, since unlike UD plies, fiber bundles are not planar, rather they are constantly alternating. A consistent outcome was obtained by Espadas-Escalante [28], who investigated the effects of layer shifting on the free-edge effect in woven fabrics. They revealed that in addition to the relative position of the plies, also the ply structure at the free edge (where the cut through the plies was made) is relevant.

Moreover, all approaches presented above consider only static loadings.

## 2.2 Progressive damage due to stress concentration at free edges

In the case of cyclic loading, the free-edge effect is also present and results in damage initiation and damage progression. A large number of studies showed that damage in CFRP UD laminates is initiated at free edges [29, 30, 31, 32]. For UD laminates, damage initiation occurred generally as interlaminar matrix cracking. The damage progression in such UD laminates is strongly affected by the fiber orientation and was observed in different modes (e.g transverse cracks, longitudinal splits, delaminations). Considering woven fabric a similar behavior was observed. Carlsson et al. [33] investigated woven CFRP laminates and has observed matrix cracks causing damage initiation, progressing into transverse yarn cracks. Subsequent debonding of weft bundles and longitudinal splits were observed before total failure occurred [33]. This is in agreement with the findings of Gao et al. [34] who investigated a different laminate but manifested identical damage mechanisms. The emerging damage appearance, which is exemplarily shown in Figure 1, illustrates the affected regions in classical tensile specimens.

However, damage initiation and propagation do not always result in total failure. The stress concentration at the free edge may be altered as progressive damage develops. This can result in stress relief and stress redistributions that can counteract damage progression or relocate damage progression to other locations, as described by McCarthy et al. [35].

This emphasizes the importance to fully understand the free-edge effect and to account the stress concentration that arises thereby when designing structural components.

Among other structural features that influence the free-edge effect, free edges of structural components frequently show an out-of-plane waviness. Thereby introducing an additional bending moment into the laminate when e.g., tension loaded. This effect was investigated by the author's institute by means of tension-tension fatigue loaded thin 2D plain-woven CFRP laminates containing an out-of-plane waviness. It was shown that the waviness, which extends over the entire width, increased the free-edge effect and triggered damage initiation and damage propagation. Performed experimental testes and numerical computations revealed relevant stress components that were responsible for damage through superposition of the waviness and the free edge. However, for detailed information see Heinzlmeier et al [36].

## 3 Stress concentration at notches

Another common stress concentration that occurs within structural components is that induced by notches. These notches can originate from design features, or from damages caused in regular operation (e.g. scratches, cracks). Again, these have to be taken into account during the design phase in order to avoid premature failure.

### 3.1 Stress concentration at notches under static loading

In contrast to metallic components, where stress concentrations can be expressed using stress concentration factors (SCF), CFRP components require different methods since a size effect is present [37, 38, 39]. This size effect is associated to a notch size dependent strength and led to alternative approaches, like the frequently used Point Stress Criterion (PSC) or Average Stress Criterion (ASC), as proposed by Whitney and Nuismer [40]. In this way, the load-bearing capacity of components weakened by such stress risers (notches) is calculated, including the size effect. Both imposed criteria allow a straightforward assessment of structural integrity. However, these approaches were found to yield quite conservative results and improved techniques were developed [41]. Aronsson and Bäcklund [42] came to a similar conclusion as Karlak [41], undertaking experimental and numerical investigations on cracked laminates under static loading. They proposed the use of a numerical damage zone model, instead of the PSC and ASC, as this provided the best agreement for their tests.
Experimentally, Harris and Morris [43] examined the fracture strength of tensile loaded notched laminates (various lay-ups considered). The notched laminate strength of the center-cracked specimens could be predicted with a numerical Dugdale model using the crack-opening displacement. They also observed extensive notch-tip damage in form of matrix cracking and delaminations prior to fracture.
This extensive notch-tip damage was used by Beaumont in their investigations, as they proposed a new approach in which a damage-based notched strength model was developed [44, 45, 46]. Similar to the free edge, FE is a suitable method to analyze the stress concentrations of notches. Using a cohesive zone model, Waas et al. [47] compared their experimental tests on woven fabrics and obtained acceptable results. This is in line with the findings of Tan [48], who also predicted the failure (size and location of delamination) of notched CFRP laminates with a cohesive zone model implemented in Abaqus CAE. Likewise, this approach was used to detect the initiation of damage in double-notched shear experiments, in which the degradation of stiffness was also taken into account [49].
As an alternative to cohesive zone models, linear elastic fracture mechanics (LEFM) is adopted to describe the damage progression originating from notches [50, 51, 52, 53]. But

as mentioned by Rafiee [49], this approach is limited to damage progression. Therefore, an initial damage has to be inserted into the generated model.
Alongside these studies, a significantly larger number of investigations exists dealing with further notches, e.g openings of various shapes [54, 55], or different kinds of surface scratches [56, 57].
To simplify the complex behavior of stress concentrations induced by certain notches and to obtain appropriate notched strengths of CFRP structural components, a circular hole is usually considered to be a standardized notch shape [35, 63, 64]. Additionally, in high performance applications such holes are often present (e.g. inspection holes, fastener holes). Hence, a special attention is placed on the stress concentration caused by a circular hole.

### 3.2 Progressive damage due to stress concentration at notches

Under cyclic tensile loading a dependency of the notched strength on fibre-type, notch-depth, notch-shape, load type, load-sequence and damage size was observed [58, 59, 60, 61, 62].
In alignment to the standardized processes mentioned in the preceding section, numerous experimental investigations were performed with the aim to describe damage behavior related to this stress riser. Hallett et al. [65] revealed a strong dependence of damage behavior and failure stress upon hole size and layup for UD laminates. This is consistent with observations of other notches. Moreover, they characterized the damage with non-destructive testing methods and compared the measured subcritical damage with FE simulations, based on a cohesive zone model.
A similar approach was taken by Aymerich [62], who examined the effects of subcritical damage on residual strength using digital image correlation and X-ray measurements. They found a damage-dependent rise of the residual strength [62]. This can be attributed to interlaminar damage and the resulting stress relief. With increasing damage size, the stress relief also increases, causing greater notch strength [43, 35]. However, this was not quantified.
Further experimental investigations on progressive damage were performed by Aidi et al. [66], where the residual properties and corresponding damage states were assessed. Again an increase of the residual tensile strength was revealed. The underlying principles seem to follow a similar behavior as described by McCarthy [35].
But since these investigations are based on narrow specimens (following the standardized procedures), the stress concentration from the free edge (described in section 2) results in a second damage mechanism acting on the specimen. With increasing test duration, the damage propagation from the hole and free edge mutually interact and reduce the time to total failure, as the hole and the free edge are located close to each other. These observations were made by Aidi [66] and Hallett [65]. In consequence, describing the damage progression on such narrow specimens is not appropriate. Hence, a larger specimen width is necessary to avoid any interaction between the stress concentrations of the circular hole and the free edge.
This important aspect was addressed by the author's institute by contributing research at 2D plain-woven CFRP plates with holes that allowed the description of damage that originates and propagates from a circular hole without any influence of the free edge [67]. In the experimentally identified damage propagation emanating from the hole, dam-

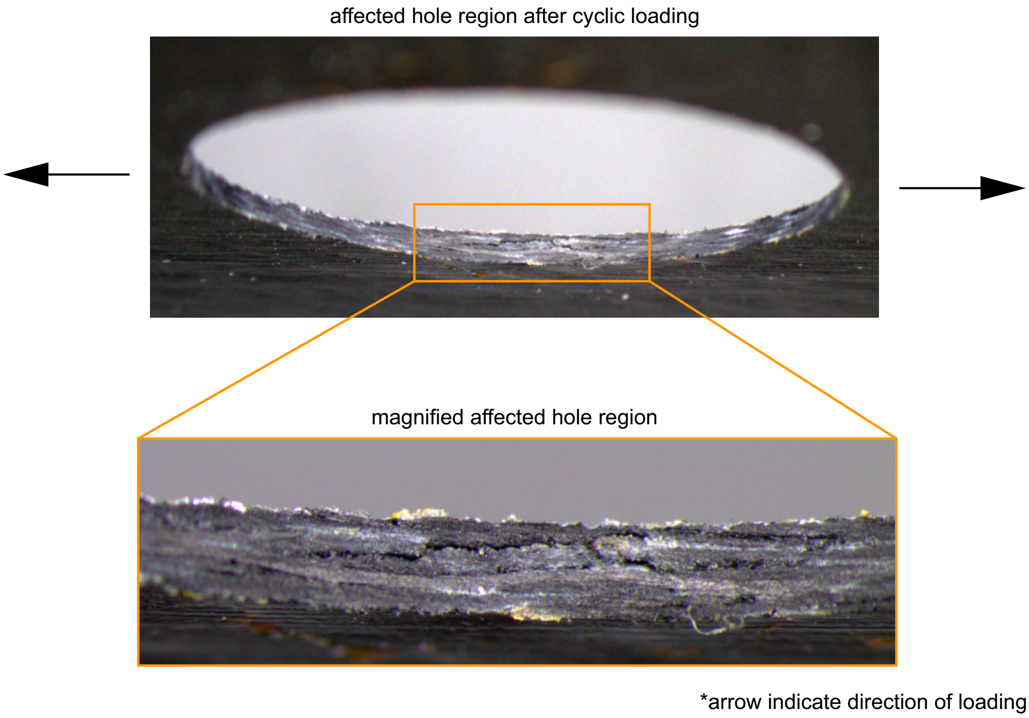


**Figure 2**: Typical damage at a hole in a plain-woven CFRP laminate under tension-tension fatigue loading.

age ceased to grow under the selected loads. This could be attributed to a stress relief [35]. Since larger specimens have been used, no redistribution of damage progression was observed, in contrast to the investigations on smaller specimens [66, 37]. Within the experiments performed at the author's institute, damage was measured optically and an empirical model was established, which could be used to describe the subcritical damage as a function of the load level [67]. During these investigations, damage to the hole as illustrated in Figure 2 appeared. To improve clarity, the same portion of the hole is shown magnified.

## 4 Conclusion and Outlook

Stress concentrations at free edges and stress concentrations at notches have a major effect on the strength of structural components. Thus, their influence needs to be fully considered so that appropriate components can be designed with respect to safety and operational reliability. During usual material characterization with narrow specimens, the free edge is present and triggers damage causing premature failure. As described, widespread delaminations can result. This changes the stress state and can cause a relocation of load to different parts of the structure with initially lower stresses.

When notches are involved, the stress concentrations of the free edge and the notch are superimposed. While this superposition is hardly noticeable in static material testing, fatigue investigations have shown a clear interaction, resulting in premature failure. Using specimens with larger width compared to laminate thickness and notch size allows the description of subcritical damage independently from the free edge. This was demonstrated by the author's using a simple cyclic tension-tension loaded plate with a hole,

where resulting progressive damage shown to be limited to areas of stress concentration at the hole.
However, under operational conditions, load spectra containing variable amplitude loads are present, and future investigations shall focus on damage progression following load adaptation, utilizing an approach recently published by the author's. Furthermore, structural health monitoring methods will be applied for, (i) real-time damage observation during fatigue testing of plates with a circular hole, and (ii) collect data for potential future damage diagnosis during operation.

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