Resolving the effects of vent hole on the strength of damaged composite laminates in resin-injection repair method

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Abstract. Resin-injection repair method has been proposed for use in repairing barely visible impact damage (BVID) in carbon fibre reinforced polymer composite (CFRP) laminates. This method targets the damaged region by drilling a hole, to a predetermined depth, within the crack region for injecting the resin. To facilitate the flow of the resin into the cracks, vent holes (to predetermined depths) are also created within the periphery of the damaged area to enable trapped air in the cracks to escape. Clearly, the presence of vent holes is expected to weaken the laminate but to what extent would the vent holes compromise the mechanical properties of the barely visible damaged composite laminate is not clearly understood. Here, we highlight a simple study to investigate the effects of vent holes on the mechanical integrity of the CFRP laminates. The objective was to determine the mechanical properties of CFRP laminate specimens (both undamaged and barely visible damaged ones, derived from a quasi-static indentation test) with respect to the number of vent holes by subjecting the laminates to in-plane compression to rupture. The mechanical properties of both vent-holed undamaged and damaged specimens were statistically analysed to assess for evidence of differences in the mechanical properties of the specimens with varying number of vent holes. Multi-scale image analysis was carried out to assess the in-plane compression-led rupture morphology of the site of the vent holes.

Introduction

Carbon fibre reinforced polymer matrix composites (CFRPs) are materials comprising carbon fibres (typically running continuously from one end of the material to the other) unidirectionally embedded in an epoxy matrix[1]. By stacking layers of these unidirectional composites in different directions, this can result in a composite laminate with excellent in-plane properties as well as high specific stiffness and strength[2]. Thus, CFRPs are increasingly deployed in mission-critical engineering structures—where metal-based structures once dominated—which in turn translates to greater weight savings[2].

However, this laminate structure is also susceptible to defects in the form of localised delamination or impact damage to the surface, resulting in inter-laminar fracture as well as delamination that is seen at the microscopic level [3]. Inter-laminar fracture or delamination reduces the effectiveness of stress-transfer of the load from the fibre to the matrix and consequently compromises the mechanical integrity of the composite material [1, 4]. Delamination can occur when the laminate experiences low energy impact; delamination can also occur during cyclic thermo-mechanical loading[3].

When repairing delamination damage in aircrafts, there are several conditions to abide—such as aerodynamics and durability[5]. The common patch and scarf repairs, which do not require taking the damaged structure apart, involve applying a reinforcing patch by bonding or bolting to the composite material [5]. In the case of the bonded patch scarf repair, upon the removal of material (namely the outer undamaged plies) from the damaged area, a new composite piece structurally and mechanically compatible with the area to be patched is bonded to the area using a suitable bonding adhesive [5]. However, while these methods can normally access the damage area, one can expect that damage could occur as a result of removing the original material around the damaged region [5]. Additionally, can also expect that this method is not suitable for structures where there is a difficulty in repairing the damaged area, such as corners or edges [5].

To this end, it is recognised that more novel repair methods are needed to overcome the limitations in conventional repair methods. One such method which avoids the need to remove the outer undamaged plies involves injecting resin via an access hole (hereafter known as the resin injection hole) into the damaged area with the objective of infiltrating the delaminated layers [5]. After the resin-injection step is completed comes the curing step, which is intended to harden the injected resin in the damaged area [5]. There are many factors determining the effectiveness of the injection repair, e.g. the resin type [6-8], accurate determination of the extent of the damage[3], the resin adhesive strength (which underpins the stress transfer capacity[9, 10]), and wettability on the composite surface and viscosity [8, 11]. Of note, low viscosity is needed to ensure that the resin can adequately infiltrate into the delaminated layers after injection [8, 11]. Thunga and co-workers have proposed a novel resin-injection method that relies on (1) the use of vent holes for assisting the flow of the resin through the delaminated zone and minimizing trapped air and (2) low-pressure environment, for extracting the air in the delaminated zone via the vent holes[6-8]. While the results from their studies have shown high strength recovery[6-8], the modest number of specimens used in the study may not be adequate in fully accounting for the variability in the method and process. Additionally, since it is expected that the presence of vent holes would weaken the laminate, to what extent would the vent holes compromise the mechanical integrity of the laminate is not clearly understood. Finally, the repair work of Thunga and co-workers was carried out in the laboratory on flat laminates, which were fitted in a vacuum chamber (to assist with the resin flow) that had limited capacity for adapting to curve surfaces on airframes. This means that if the method were to be deployed for repairing BVID airframes, a radically different design of the vacuum chamber would have to be proposed.

To address these issues, we have recently embarked on a project to further explore the resin-injection method, following the method of Thunga and workers[6-8]. The main motivation underpinning this study is to investigate the structure and mechanical properties of the repaired CFRPs using the method and to gain insights that can help improve the method, i.e. ensuring good repair efficiency when it comes to implementing an in-situ repair process assisted by a flexible vacuum chamber device that we have recently proposed [12]. Here, we report on a simple study to determine the extent of the influence of the vent holes on the mechanical integrity of the laminates.

Methods

Specimens of CFRP laminate (length 160mm; width 100mm; thickness 4mm) were purchased from a local supplier. These were divided into two groups for further treatment; one group was damaged by subjecting to quasi-static indentation to create barely visible impact damage. The damaged specimens were examined under infrared thermography to assess for the extent of the damaged region; the findings were needed for determining the region where the vent holes would be drilled. Next, both groups, i.e. the damaged and undamaged specimens, were then treated to drilling to create resin-injection holes and varying number of vent holes. Thereafter, the undamaged and damaged specimens were subjected to in-plane compression to determine the residual mechanical properties, namely strength. In all cases, multi-scale image analysis was carried out to examine the damage morphology. Statistical analysis was carried out to assess for evidence of effects of vent hole number on the mechanical properties of the laminate.

Results & Discussion

At the edge of the vent hole, the fine structure showing two kinds of morphological features attributing to fibre pull-out and matrix cracks. While the edge of the vent hole has a near-circular morphology closer examination revealed matrix delamination propagating to a depth on order of magnitude estimate of 20 microns. These failure modes could affect the material response to different mechanical loading such as compression and tension. With regards to the BVID specimens, one-factor ANOVA revealed that the strength of the damaged specimens was significantly affected by the number of vent holes ($P < 0.05$). Tukey Post-hoc comparison analysis revealed that the higher the number of vent holes, the lower the strength. To assess if the sensitivity of the strength due to vent hole number depends on the mechanical condition (damaged versus undamaged) of the laminate-as well as if the effects on the strength due to mechanical condition depends on the vent hole number-further analysis by two-way ANOVA was carried out. It was revealed that there was no evidence of effects on the strength due to interaction between the factors ($P > 0.05$). We concluded that there was evidence of effects of vent holes on the strength of damaged laminates. However, vent holes did not affect the strength of undamaged laminates.

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