# METAL REINFORCEMENT AROUND FASTENER HOLES IN COMPOSITES

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**Keywords:** Hybrid joint, Bearing strength, Insert, Stacked, Patch

## Abstract

One way of improving the load capacity of bolted joints in composite components is to use metal inserts locally at the holes in order to reduce the bearing stress. In this paper an innovative local reinforcement concept is introduced where metal inserts are implemented in the form of stacked patches at the holes in order to improve the bearing strength of the composite. After doing some initial tests and a parameter study, some specimens with optimized stacked patch inserts were designed and tested. The specimens with optimized inserts show 50-60% improved bearing strength in pin-loaded tests which corresponds to a potential weight reduction of about 30%. These very promising results indicates that the efficiency of joints in composites can be improved significantly.

## 1. Introduction

The need for lightweight products is increasing due to higher performance demands but also due to finite resources and environmental concerns. A significant amount of money is invested on research related to fuel consumption by the aviation industry. One study indicates that a weight reduction of 1 kg for a commercial aircraft results in a fuel saving of more than 1000€ during its life cycle [1]. On the other hand, some targets have been set for coming years by the aviation industry in order to reduce emissions. For example, by 2050 the $CO_2$ emissions should be reduced by 75% compared to the levels in 2000. This means that there needs to be a 10% reduction in the weight of aircraft and aircraft engines every 10 years at a minimum. As a result, considerable research efforts are needed to make design and manufacturing of lightweight aircraft components more efficient.

The primary joining technique currently used for connecting different composite components in aerospace applications is mechanical fastening. However, using mechanical fasteners like bolts for composite materials is less straightforward than for metals. In fact, achieving a satisfactory joint efficiency in composite structures is a challenge for designers because composite laminates have high notch sensitivity, are anisotropic and have relatively low bearing strength. Increasing the efficiency of joints in composite laminates would potentially increase the efficiency of the composite material since the required thickness of the whole laminate could be reduced. Many methods for increasing the efficiency of composite joints have been suggested and analyzed. One of the most effective ways to improve the load capacity of bolted joints is local hole reinforcement of composite laminates with high-strength metals. Previous research activities [2–5] have showed that the efficiency of composite joints can be considerably improved by altering the composite plies in the joining area with high-strength Titanium sheets. The present paper introduces a new way of replacing composite plies with metal sheets at the hole-perimeter in order

Excerpt from ISBN 978-3-00-053387-7

to increase the specific strength (strength per weight) of a joint. An optimized implementation of the patched metal insert results in a joint with high bearing capability, which is essential to obtain a high joint efficiency. The paper presents an experimental study where specimens with different metal inserts are manufactured and tested in order to find suitable insert configurations.

## 2. The reinforcement concept

Metal inserts are implemented in the form of stacked patches at the locations of the holes in order to improve the bearing strength of the composite. A picture of a specimen, and a schematic sketch of the insert configuration are shown in Fig. 1(a) and 1(b), respectively. The core of the concept is the idea to separate the bearing stress problem from the hybrid metal-composite joint problem and handle the two at different interfaces rather than at the same. In the way it is implemented the concept also provides a number of other benefits. One is the great potential for weight saving in cases where the bearing strength drives the laminate thickness. In addition, the presented concept enables clamping pressure by the fasteners and thereby joints carrying load also by friction. Finally, layer-wise integration of the inserts in the pre-preg laminates during curing, and simpler drilling operations compared to co-drilling of metal-composite interfaces are additional advantages.

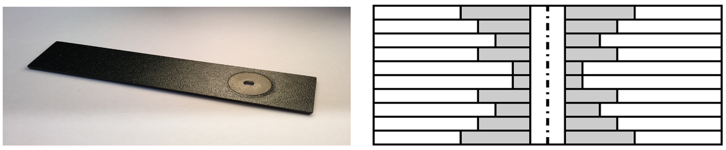
(a) (b)

**Figure 1.** A specimen with a metal insert (a) and a schematic sketch of an insert (b)

## 3. Method of approach

The strength of metal-composite finger-joints was examined by tensile tests and the bearing strength of holes reinforced with stacked metal inserts were investigated by pin-loaded tests (Fig. 2). A number of specimens were also manufactured without inserts to be used as reference.

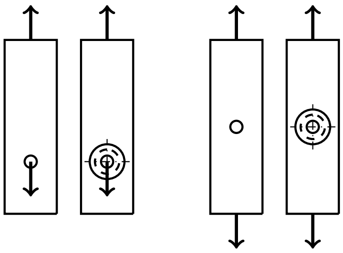
(a) (b)

**Figure 2.** Pin-loaded reference, and with an insert (a) and tensile reference, and with an insert (b)

Inserts were built from circular stainless steel patches of two alternating diameters, stacked in various sequences, constituting the simplest possible manifestation of the concept. The patch thickness was

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about twice the ply thickness. All specimens were produced as flat laminates and then cut and drilled to final dimensions. A sketch of the pin-loaded specimens is shown in Fig. 3. The tensile specimens had the same dimensions as the pin-loaded ones but with the hole centered in the test cupon. The edge distance of the pin-loaded specimens was 36 mm.

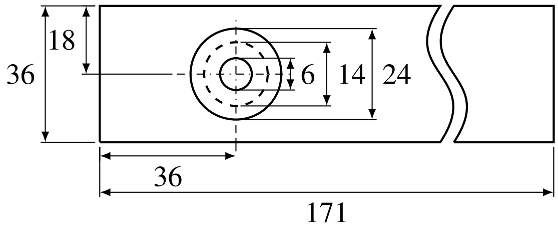

**Figure 3.** The dimensions of the pin-loaded specimens in mm

The inserts were built layer-wise while stacking the prepreg plies, with thin adhesive films between the metal patches. The patches were placed in holes, cut in the prepreg plies in advance, and co-cured together with the prepreg plies. Varying stackings of patches and prepreg plies, and different insert configurations were designed and tested.

Stainless steel EN 1.4310/AISI 310 was chosen for the metal patches due to its availability but other materials could also be of interest for the concept. The laminates were manufactured using prepregs of high tensile strength carbon fibers and an area weight of 134 g/m$^2$. It contained a HexPly 6376 matrix with a fiber volume fraction of 60%. The nominal mechanical properties used for the HTS/6376 134gsm prepreg were $E_1 = 135, E_2 = 8.5$ and $G_{12} = 4$ GPa, where the subscript 1 refers to the longitudinal (fiber) direction and subscript 2 refers to the transverse direction.

Three consecutive test series were performed, categorized as initial pin-loaded tests, tensile tests on simplified configurations, and pin-loaded and tensile tests on optimized configurations.

### 3.1. Initial pin-loaded tests

A few pin-loaded tests were initially performed to check the feasibility and the potential of the reinforcement concept. Two specimens with metal inserts and three corresponding reference specimens without inserts were tested.

### 3.2. Tensile tests on simplified configurations

A parameter study was performed on some simplified (non-optimized) insert configurations in order to study the effect of different parameters such as stacking sequences, and insert configurations in a separable way. Two different types of specimens were designed and tested in tension with either strip or circular inserts as shown in Fig. 4. The width of the long and short metal strips were 24 and 14mm, respectively. Specimens were made of 16 pre-preg plies, divided into 4 blocks of 4 plies each with the same fiber orientation. 4 specimens per case were tested.

The experiments were conducted to characterize the tensile strength of the metal-composite interfaces. The samples with strip inserts were intended to provide general understanding of the strength of the metal-composite finger-joint and the results of samples with circular inserts were to confirm that the

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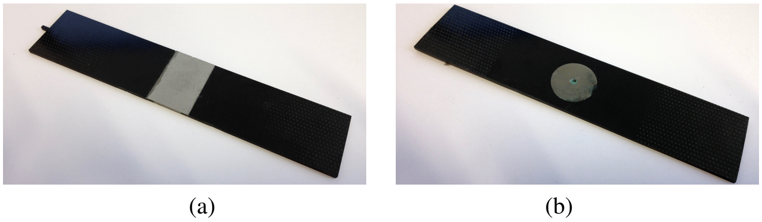


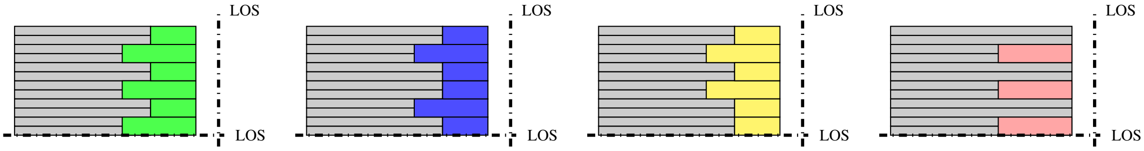
(a) (b)

**Figure 4.** Specimens with either strip (a) or circular (b) inserts

understanding was also valid for circular inserts although there are then some other parameters that affect the strength of the finger-joints too.

### 3.3. Pin-loaded and tensile tests on optimized configurations

Based on the knowledge gained from the parameter study, some specimens with optimized inserts were designed. Two insert configurations were optimized for good and deliberately poor performance, aiming to verify the conclusions from the parameter study. The ”Good” and ”poor” configurations had identical insert geometry (Fig. 5 (a)) but different stacking sequences. 4 specimens per configuration were built from 24 prepreg plies and 12 metal patches. The stacking sequence of the good case was $[+45/0/-45/90]_{3s}$ whereas for the poor case the stacking sequence was simply turned 90° from the good case. In addition to the good and poor configuration, three other insert configurations were designed by varying the stacking of metal patches and prepreg plies. These configurations were made from fewer metal patches and labeled as I5, I6 and I7, shown schematically in Fig. 5 (b), (c) and (d).



(a) (b) (c) (d)

**Figure 5.** Insert configurations of ”good” and ”Poor” cases (a), I5 (b), I6 (c) and I7 (d)

## 4. Results and discussions

### 4.1. Initial pin-loaded tests

The specimen failed due to bearing (yield) failure at the hole in the inserts and a 23% improvement of the ultimate bearing strength was achieved. This proof of concept was the incentive for the following test series.

### 4.2. Tensile tests on simplified configurations

Two different types of failure were observed during tensile testing of specimens with strip inserts, premature failure and finger-joint failure (Fig. 6). Premature failure emerged as rupture of the composite

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material at relatively low loads whereas finger-joint failure happened at considerably higher loads. Specimens showing premature failure did obviously not provide much information about the strength of the finger-joints as such, but indicated that the insert was poorly matched with the composite material.

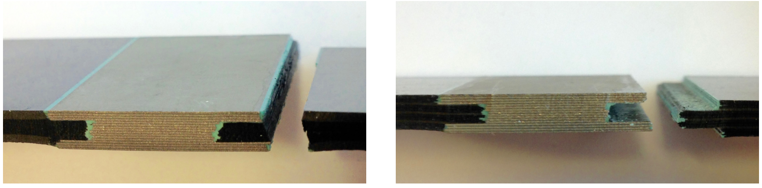

(a) (b)

**Figure 6.** Premature (a) and finger-joint (b) failure of simplified specimens

The strength of the simplified specimens with strip inserts is presented in Fig. 7, together with corresponding failure modes. Premature failure and finger-joint failure are schematically indicated with red dashed lines in the sketches of Fig. 7.

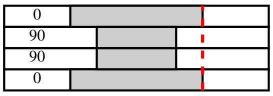
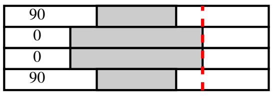
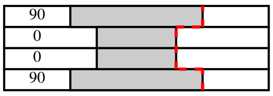
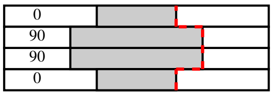
| Name | Strip insert sketch | Prediction of failure | Experimental tensile strength [MPa] |
|---|---|---|---|
| Strip 1 |  | Premature failure | 41 |
| Strip 2 |  | Premature failure | 44 |
| Strip 3 |  | Finger-joint failure | 147 |
| Strip 4 |  | Finger-joint failure | 177 |

**Figure 7.** Sketches, failure modes and tensile strength of simplified specimens

Looking at the stacking sequences and insert configurations in Fig. 7, it can be concluded that poor butt-joint strength of metal to 0°-plies contributes to concentrated loads in adjacent plies and seems to be associated with premature failure. The strength of the finger-joints is considerably higher when 0°-plies meet longer metal strips with overlapping interfaces.

The results of the tests on simplified specimens with strip inserts showed that contribution to the strength from butted parts of the joint is negligible in comparison with the contribution from lapped parts. In addition the total strength of metal-composite joints, depends strongly on the total overlapped metal to 0°-ply area.

Tensile tests of specimens with circular inserts measure the strength of the finger-joint between the metal

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patches and the composite and also indicate the amount of by-pass load that can be transfered around the hole. The results from the tensile tests with circular inserts were consistent with the conclusions made from the strip insert tests.

## 4.3. Pin-loaded and tensile tests on optimized configurations

### 4.3.1. Pin-loaded tests

The load-displacement graphs of a reference specimen and a specimen with the ”good” insert configuration are shown in Fig. 8. The results from the pin-loaded tests were in general strikingly consistent with very low scatter as shown in Fig. 9. The optimized good case showed 60% strength improvement compared to its reference while the ”poor” case showed only 12% improvement of the ultimate load. The ”good” case showed bearing failure and the ”poor” case showed premature failure as shown in figure 10.

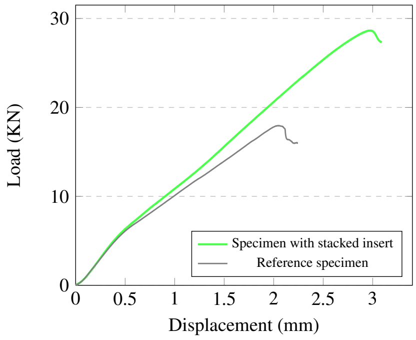

**Figure 8.** Load-displacement graphs of a reference specimen and a specimen with a ”good” insert configuration

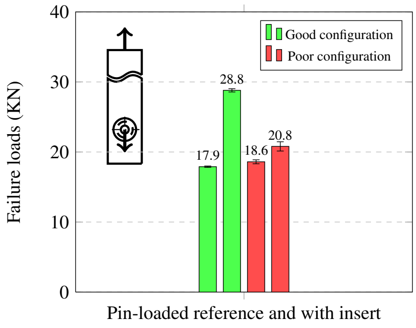

**Figure 9.** Bearing failure loads of the good and poor cases

The pin-loaded test results for I5, I6 and I7 configurations showed about 50% improvement in bearing strength as shown in Fig. 11. The standard deviations were again very small and the final failure mode was bearing failure for all I5, I6 and I7 specimens. Comparing the I5 and I6 configurations (Fig. 5 (b) and (c)), it can be concluded that minor deviation from an even patch distribution does not affect the bearing strength of the insert much, if the matching with plies is similar. The relatively larger overlap area of the metal to 0°-ply lap interface in the I7 configuration does not increase the bearing strength.

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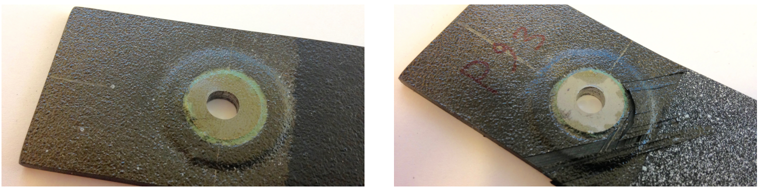
(a) (b)

**Figure 10.** Bearing failure of the good (a) and premature failure of the poor (b) configurations

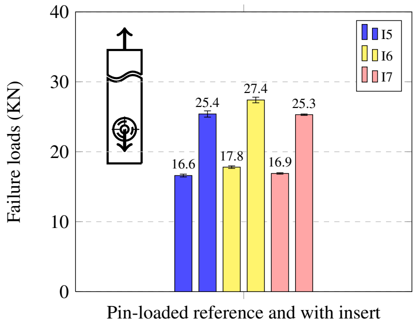

**Figure 11.** Bearing failure loads of I5, I6 and I7

### 4.3.2. Tensile tests

The tensile strength of the good configuration came out 13% lower than for the reference case as shown in Fig. 12. The tensile strength of I5 was considerably higher while I6 was slightly lower than for the reference case. It should however be mentioned that the optimization was performed for improved bearing strength, not for by-pass load capacity of the specimens.

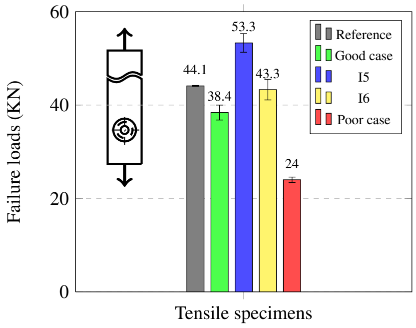

**Figure 12.** Tensile results for optimized configurations

## 5. Conclusion

It is clear that proper implementation of metal inserts through taylored stacking of patches at the holes of composite laminates can improve the strength of pin-loaded holes tremendously. The weight penalty for the presented cases is about 5 g per bolt (for a 6 mm bolt diameter) and a 50-60% strength improvement is obtained. As a rough estimation of the weight saving potential of the reinforcement concept, a composite

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reference with the bolt hole diameter, $d$, thickness, $t_r$, and failure load, $F$, is considered (Fig. 13). Assuming improved bearing strength by 50% and the thickness of the laminate with insert, $t_i$, being designed for equal failure load, then

$$\frac{F}{dt_i} = 1.5\frac{F}{dt_r} \Rightarrow t_i = \frac{t_r}{1.5} \tag{1}$$

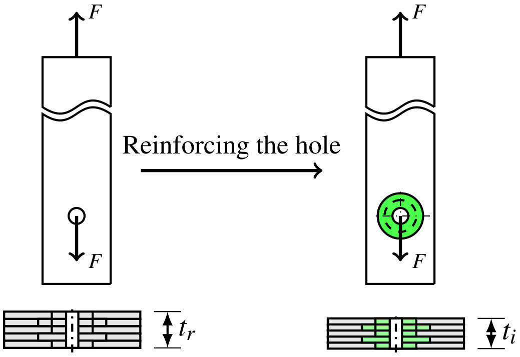

**Figure 13.** Rough estimation of weight saving

and a potential thickness reduction of 33% can then be achieved. These very promising results indicate that the efficiency of joints in composites could be improved significantly and thereby reduce the weight of composite parts and even structures, since their thickness in many cases is driven by requirements on the joints. Further analysis and optimization activities are foreseen to bring the concept closer to industrial implementation.

## 6. Acknowledgments

The work presented in this paper was funded by the European Locomachs project (FP7 314003) and supported by SAAB AB.

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