RTM COMPOSITE LUGS FOR HIGH LOAD TRANSFER APPLICATIONS

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Abstract

This paper presents the work performed on composite RTM lugs designed for aerospace applications. The objective was to get information on stiffness, strength and failure mode of both the lug and the joint between the lug and main structure.

The main design driver after structural requirements was the use of cost effective manufacturing methods. The selected concept was designed, manufactured and structurally tested.

The analyses were performed using finite element method. A steel pin together with contact definition was modelled to apply the loading to the lug.

The test lugs were manufactured with the resin transfer moulding (RTM) technique. The materials used were carbon fibre fabric G926 and epoxy resin RTM6. The surrounding structure was represented by face sheets, a spar and a rib behind the lug.

The test specimens were loaded with straight tension loading. The lug strength exceeded the expected value because of conservative design methods. However, the bonded joint between the lug and the surrounding structure failed at much lower load than expected.

Based on the work done it can be concluded that 1) the proposed lug geometry is a feasible solution for high load transfer applications, 2) the peel strength of the adhesive in the secondary bonded lug plays an important role in the ultimate strength of the lug and 3) the bonded joint with the lug and the surrounding structure can be repaired and original strength is possible to retain.

1 Introduction

Flight control surfaces of a modern aircraft are made of composite structures. Typically the main load carrying lugs are still made of metallic materials. One reason for this is the lack of commonly agreed design methods for composite lugs. As the level of integration in structures increase, the need for composite lugs becomes evident. In addition, by using composite lugs the thermal mismatch and galvanic corrosion can be avoided.

In serial production of aircraft structures the manufacturing costs play an important role. One way to reduce recurring manufacturing cost is to increase the level of part integration in structures and hence to reduce the time spent on assembly.

Resin transfer moulding (RTM) is an ideal manufacturing method if high level of integration and small tolerances in part production are to be met. It is a well known fact that typically tooling costs in RTM are higher than in other composite manufacturing methods. However, RTM is especially suitable for complicated parts with several interface surfaces.

This paper presents a composite lug construction that is designed to be used as a main load carrying component in flight control surface structures of a commercial aircraft. The purpose was to find out a structural concept that meets the structural requirements, enables the integration with other parts of the structure and has low recurring manufacturing costs.

2 Lug Design

The RTM lug under investigation was designed to be used in control surfaces of a commercial civil aircraft. The control surface was designed to be a fully integral composite structure. In the previous research the strength of the composite lug was evaluated [1]. In this study also the surrounding structure was considered.

The reference structure for the design was A380 spoiler number 1. The space allocation requirements were less restrictive but loading conditions and other structural performance requirements were the most challenging ones.

The main design drivers for this specific lug were 1) the lug must sustain the design ultimate load 2) the joint between the lug and the surrounding structure must sustain the design ultimate load and 3) the manufacturing concept must be simple, cheap and allow the use of net-shaped performs.

The selected lug concept is a flat laminate and the shape of the lug is machined. The tensile loads from the lug are transferred to face sheets using flanges. Similar flanges are used to transfer shear loads from the lug to the front spar. In case of an integral structure this joint can be considered as a bonded joint where the bondline is formed by a resin rich layer. The geometry allows the use of bolts also. Therefore, the lug is also possible to be designed as a replaceable part without major changes in geometry.

The bolted joint designed for this lug was a three-row bolted joint. Only the joints between the lug and two face sheets were considered. Therefore, the total amount of bolts in one lug was 12.

2.1 Geometry

The lug consists of three laminate parts. Two of them are mirror symmetric. These two parts have flanges to form a joint between the lug and the surrounding structure. The third part is flat. The purpose of the third part is to increase the thickness and load carrying capability of the lug. The main dimensions and the illustration of different parts in the lug are presented in Figs. 1 and 2. The thickness of the middle part is half of the total thickness of the lug.

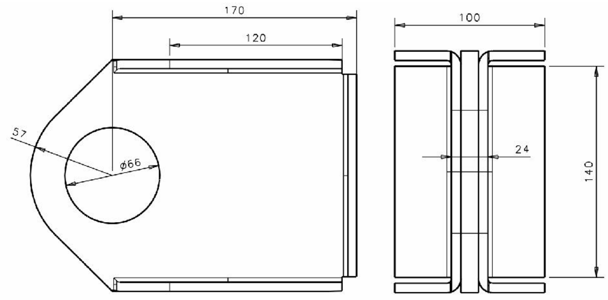

Fig. 1. Lug geometry and main dimensions

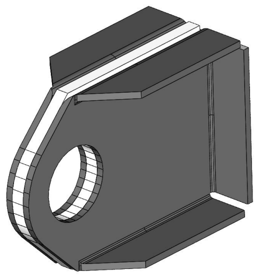

Fig. 2. Isometric view of the lug

2.3 Materials and Laminate Structure

The materials used were bindered Hexcel G926 fabric, 5H satin and Hexcel RTM 6 resin. Both materials are qualified for aerospace use. The lug consists of two different types of laminates: outer parts with flanges and the middle part. The fibre orientations for both laminates are presented in Table 1.

Table 1. Laminate structures in lug parts.

	0/90	±45	Plies	Thickness mm
Outer parts	44%	56%	18	6.27
Middle part	42%	58%	31	10.85

For secondary bonding Epibond 1590 two-component paste adhesive was selected. In order to take actual loading conditions into account some test lugs were equipped with a double roller bearing Minebea ASDR20V-603. The bearing was mounted to the lug using a steel bushing. The bolt type used was HL12VAZ10-12. The material is titanium and the bolt diameter is 8 mm (5/16”).

The material properties for the analyses were estimated based on quasi-isotropic laminated tests in ref. [2]. The values are presented in Table 2.

Table 2. Ply properties used in the analyses.

Property	Value
E_1	67.3 GPa
E_2	67.3GPa
G_{12}	5.5 GPa
ν_{12}	0.03
σ_{1t}	1050 MPa
σ_{1c}	800 MPa
σ_{2t}	1050 MPa
σ_{2c}	800 MPa
τ_{12}	80 MPa

3 Lug Analyses

The behaviour of different test specimens was analyzed using finite element method. The analysis type was linear static. When lug strength was estimated, a contact was defined between the lug hole and the steel pin. When the global behaviour of the specimen was estimated, the contact was replaced with rigid links to reduce the analysis time. All analyses were made using I-DEAS [3]. The laminate analysis was made using ESAComp [4].

3.1 Finite Element Model

Half of the specimen was modelled using parabolic solid bricks. The adhesive layer was included and bolts were modelled using beam elements. One of the models used in the analysis is presented in Fig. 3.

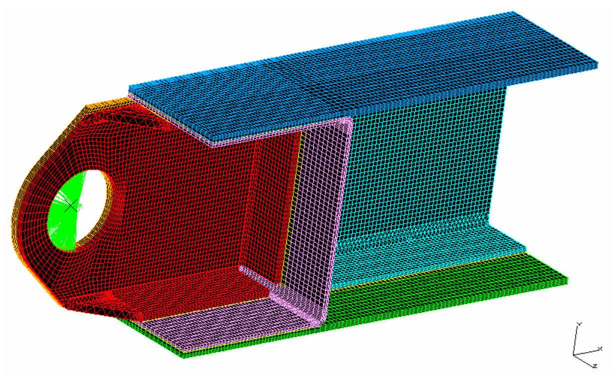

Fig. 3. Solid FE-model used in the analyses.

3.2 Results

The results of the FE-analyses are presented in Figs. 4-6. The load in the contour plots corresponds to 200 kN loading in the test. Failure loads are estimated based on two different failure modes: tensile failure and shear failure. The corresponding maximum strains are shown.

The strains in the lug are obtained from the contact model. The contact was defined around the steel pin and the lug. The size of the steel pin used in the analysis includes also the bearing and the bushing. Therefore, the bearing was modeled as solid steel.

Based on the analysis performed and the material properties in Table 2, the estimated failure load for the lug is 315 kN and the failure mode is expected to be tensile failure of the lug, the same that was found in the previous lug tests [1]. The effect of bearing was unknown.

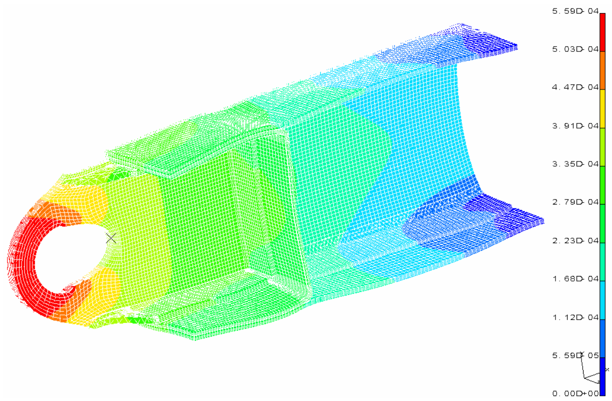

Fig. 4. Deformation results of the test specimen.

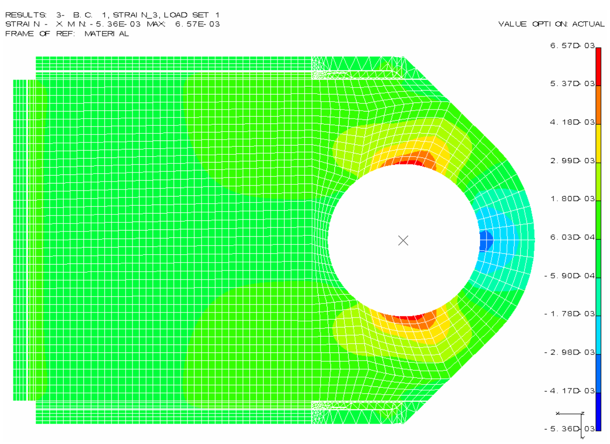

Fig. 5. Normal longitudinal strains in the lug.

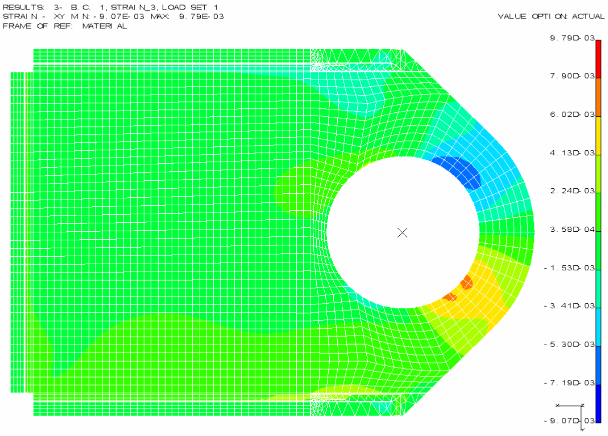

Fig. 6. Shear strains in the lug.

4 Lug Manufacture

The lug was manufactured using resin transfer moulding (RTM). The original plan was to manufacture a fully integrated lug with a single injection shot. However, to reduce the mould costs, it was decided to manufacture the middle and outer lug parts separately and to use secondary bonding. The shape of the lug was machined.

4.3 Preforming

The carbon fabric layers were cut using an ultrasonic cutter. The middle lug is a flat laminate and its lay-up is a straightforward task. The outer lug parts were preformed as an open sided box. After cutting, the flat layers were laid on top of the mould with the help of positioning holes. To preform the laminate the mould was closed and heated. The injection mould was used for preforming. Therefore, there was no need for opening the mould before injection other than checking the quality of the preform. The preform was not trimmed. The preform for the outer lug parts is presented in Fig. 7.

Fig. 7. Preform for the outer lug parts.

4.3 Tooling and Injection

The injection mould used for the RTM lug is presented in Fig. 8. The mould material is steel. The outer lug parts with flanges are made in one end of the mould and the flat middle lug part is made in the other end of the mould. Injection channels are positioned around the mould. All lug parts are injected and cured in one cycle.

The mould was mounted in a press and heated with resistance thermal element. Injection temperature of the mould was 120 ºC and the initial curing was done at 160 ºC. The free standing post-cure was done at 180 ºC. The injection pressure for lug parts was 2.5 bars.

Fig. 8. Tooling for the lug parts.

4.4 Assembly

After injection the box was cut into two producing both left and right outer lug parts. The outer lug parts were bonded together with the middle lug part (Fig. 9) and the final shape was machined as shown in Fig. 10.

Fig. 9. Bonded lug structure before machining.

Fig. 10. Machining of the lug shape.

Fig. 11. Finished test specimens.

5 Testing

The purpose of the tests was to find out the failure load and failure mode of the composite lug and the load carrying capacity of both bonded and bolted joint between the lug and the surrounding structure.

5.1 Test Specimen

The test specimen consists of the RTM lug, front spar, rib and two face sheets. The front spar is a single C-section and the rib consists of two C-sections bonded together. The laminate structure in both cases is the same as in the outer lug part. The face sheets are flat laminates made of M21/T700 prepreg tape. The laminate thicknesses were: front spar 3.9 mm, rib 2×3.9 = 7.8 mm and face sheets 4.6 mm.

Altogether five different specimens were manufactured and tested with various configurations: with and without bearing, with bolted joint and bonded joint and after an impact damage. The specimen configurations are presented in Table 3. As an example two specimens with bearings are presented in Fig. 11.

Table 3. Configurations of the test specimens

	Bearing	No bearing	Bonded joint	Bolted joint	Strain gauges
Lug 1	×		×		
Lug 2	×			×	
Lug 3		×	×		
Lug 4		×		×	
Lug 5	×			×	×

5.2 Test Arrangement

The test arrangement is shown in Fig 12. All specimens were tested in uniaxial static loading. The direction of the loading was a straight tension. The test fixture was attached to the specimen using four M16 and twelve M12 bolts. Two out of five specimens were equipped with strain gauges. The positions of the strain gauges are presented in Fig. 13.

The total number of strain gauges in lug 1 was 14. The strain gauge number 13 is in the same position as number 4 but on the other side of the specimen. Similarly the strain gauge 14 is symmetric to gauge 10. In the second specimen all mounted gauges are shown in Fig. 14.

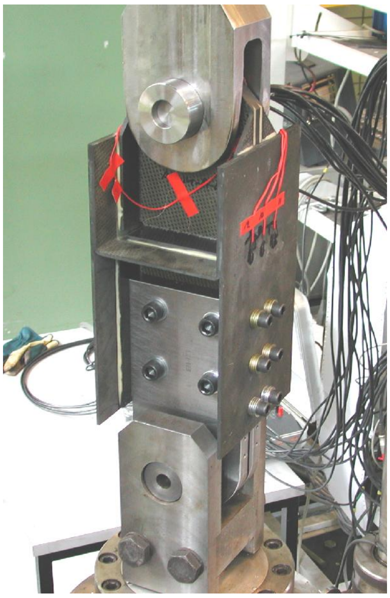

Fig. 12. Test arrangement.

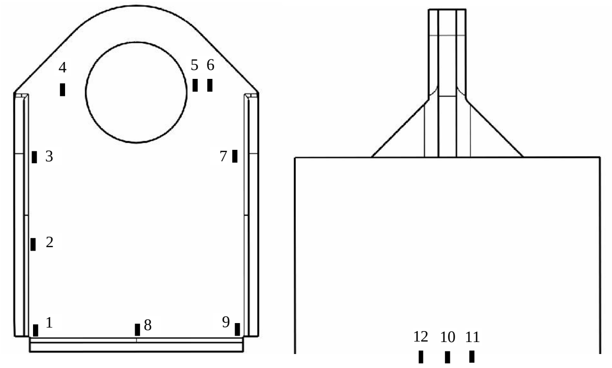

Fig. 13. Strain gauges for the lug 1 specimen.

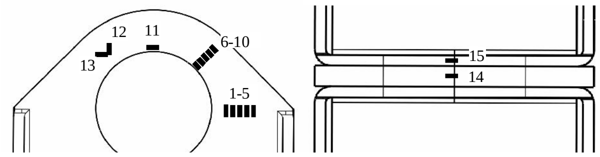

Fig. 14. Strain gauges for the lug 2 specimen.

5.2 Test Results

5.2.1 Instrumented Specimens

The instrumented specimens were loaded stepwise, i.e. the load was increased by 10-20 kN steps and the corresponding strains were measured. First the specimen was loaded to 100 kN and unloaded. Then the specimen was loaded up to failure.

The load response of the lug 1 is presented in Fig. 15. The load-strain response is highly nonlinear after 100 kN. Audible cracking was observed already at 50 kN loading when the adhesive joints between the lug and front spar and between the rib and front spar started to fail. These bondlines are subjected to tensile loads.

Fig. 16 presents the comparison between measured and calculated strains. It is expressed as the ratio between the estimation and measurements. Therefore, the value 100% represents full correspondence. The analysis was linear and the comparison is thus performed within the linear region of measurements. The calculated strains are typically approximately 10% underestimated or 30% overestimated. In some cases the correspondence is good. The gauge 8 is completely out-of-order: the strain ratio is more than 600%.

The failure of the specimen occurred at the joint between the lug and the surrounding structure at 230 kN load. Some laminate damage was observed in the lug flanges (see Fig. 17) but otherwise the lug was intact.

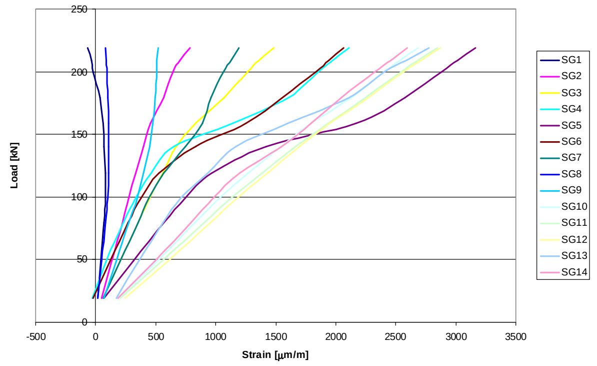

Fig. 15. Load-strain response of the first lug specimen.

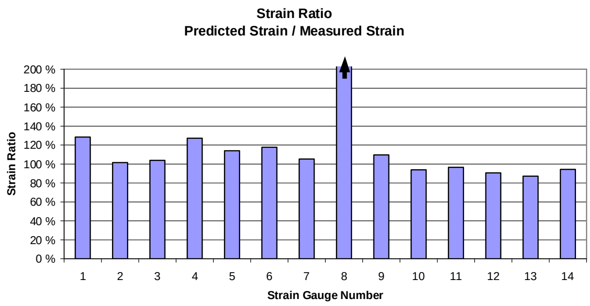

Fig. 16. Strain ratio in the first lug specimen

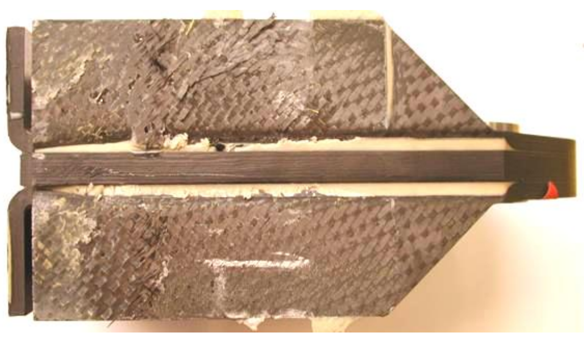
Fig. 17. Failure of the first specimen.

The load response of the second lug is presented in Fig. 18. This lug was attached to the surrounding structure with a bolted joint. The testing sequence was the same as in the previous case: initial loading to 100 kN and unloading. Then the lug was loaded to failure.

In this case the strains are more linear, but again after 100 kN some nonlinearity is observed.

Fig. 19 presents the strain ratio between estimated and measured strains. Although the load response in the second lug is more linear the accuracy of the calculation is similar to the first lug.

The failure mode was a tensile failure in the lug area as presented in Figs. 20 and 21. In the lug area the bondline between the outer lug and middle lug parts was failed. The maximum load was 397 kN i.e. significantly higher than with the first lug specimen.

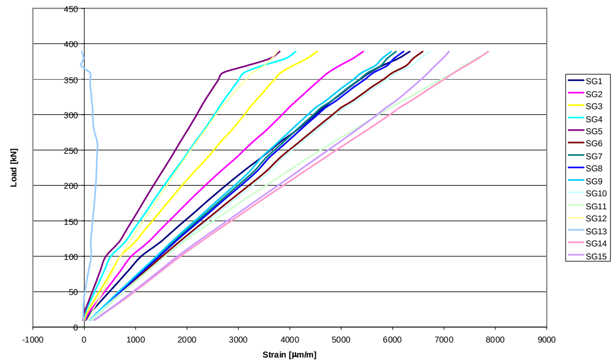

Fig. 18. Load-strain response of the second specimen.

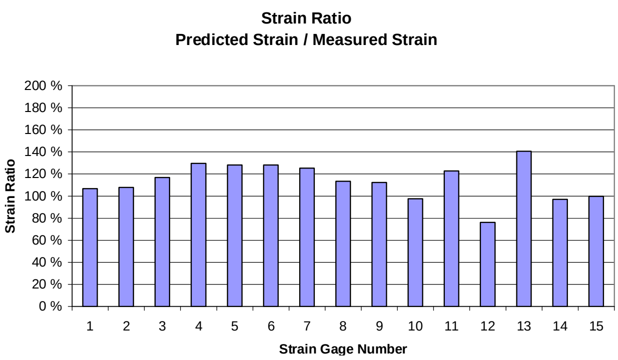

Fig. 19. Strain ratio of the second specimen.

Fig.20. Failure of the second lug specimen

Fig. 21. Debonded parts of the second lug specimen.

5.2.2 Specimens without Bearing

The purpose of the specimens 3 and 4 was to test the joint between the lug and the surrounding specimens. The same loading pin was used to avoid modifications to the test fixtures.

The specimen 3 with the bonded joint failed in the same way as the first specimen. The lug was detached from the surrounding structure. The failure load was 240 kN and some laminate damage was observed in the lug flanges. Otherwise the lug was undamaged. The failed specimen is presented in Fig. 22.

Fig. 22. Failure of the third specimen.

With the fourth specimen, the failure of the bolted joint was expected. However, the failure mode of the specimen was the lug failure. Although there was no bearing, the failure of the lug was similar to the second specimen. The failure starts as a tensile failure in the middle lug part but then propagates as a shear failure. The failed specimen is presented in Fig. 23.

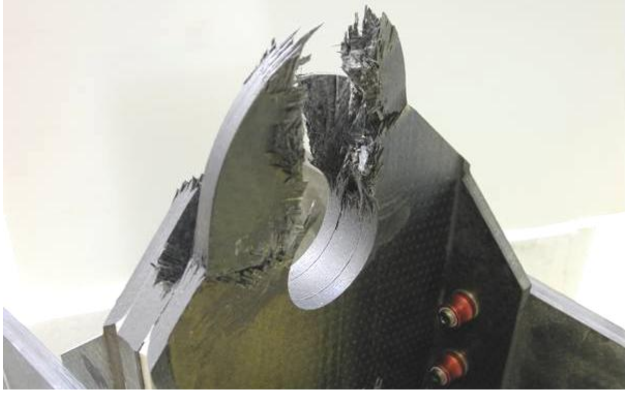

Fig. 23. Failure of the fourth specimen.

5.2.3 Impacted Specimen

The impact damage was done using a drop-weight impact testing machine. The impact energy was 76.4J. The location of the impact and the corresponding damage are shown in Fig. 24. It should be noticed that there are no delamination in the lug. The only visible damage is the dent caused by the impactor head.

The specimen was tested directly to failure. The failure load was 400 kN and the failure mode was the same as in the second specimen. The tested specimen is presented in Fig. 25. Similarly a debonding between the outer lug and middle lug parts is observed as shown in Fig. 26. The impact damage had no effect on the specimen behaviour.

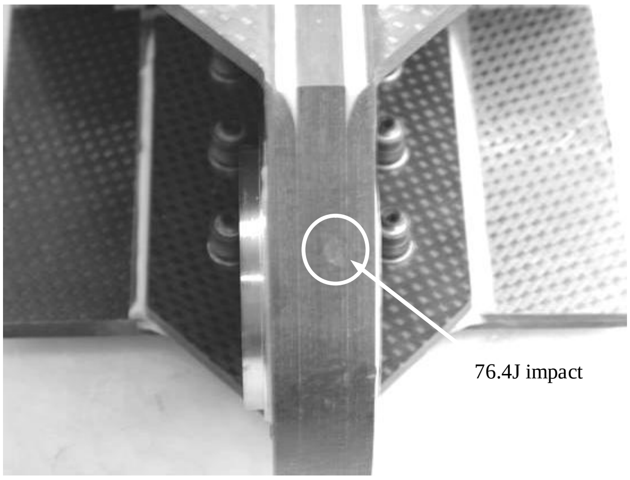

Fig. 24. Impact damage of the fifth specimen.

Fig. 25. Failure of the fifth specimen.

Fig. 26. Partially debonded parts of the fifth specimen.

5.2.3 Failure Loads and Modes

As a summary, the failure loads and failure modes for all specimens are presented in Table 4.

Table 4. Failure loads and modes for all specimens

	Failure load [kN]	Failure mode
Lug 1	230	Joint failure
Lug 2	397	Lug failure
Lug 3	240	Joint failure
Lug 4	378	Lug failure
Lug 5	400	Lug failure

5.2.4 Repaired Specimen

Because the specimens 1 and 3 with bonded joints failed without lug failure the repair of the specimen was possible. The lug was bonded to the specimen. In other damaged areas blind riveting or bolting was used as necessary. After the repair the specimen was tested to failure.

The same failure mode with repaired specimen was observed as in the first test: the adhesive joint between the lug and the surrounding structure failed at 303 kN (lug 1) and 247 kN (lug 3). The repaired lug 1 exceeded the initial failure load and the second lug reached practically the original strength.

6 Conclusions

Based on the work done the following conclusions can be made:

- The strength of the lug was underestimated because of inaccurate design values.
- The adhesive joint between the lug and the surrounding structure failed at a lower load than expected. The shear stress was approximately 13 MPa when 20 MPa was assumed in specimen design.
- The bolted joint can carry significantly higher loads than the bonded joint. Close to 700 MPa bearing stresses can be found without failure.
- The lug failed before the bolted joint. Therefore, the strength of the bolted joint was not determined.
- The impact damage had no effect on the strength of the lug.
- The Poisson effect produces tensile stress between the outer and middle lug parts causing debonding. The effect may become a significant fatigue problem in repeated loading. Also the effect of temperature must be considered if the lug is designed for actual structures.
- The analysis did not predict the behaviour of the specimen correctly. Nonlinear analysis and the use of progressive damage modelling should be used for better correspondence.
- The bonded joint between the lug and the surrounding structure can be repaired and the original strength can be achieved.
- The lug concept presented in this paper is a feasible solution for low cost and high load transfer aerospace applications.

Acknowledgements

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