FOI, Swedish Defence Research Agency, is a mainly assignment-funded agency under the Ministry of Defence. The core activities are research, method and technology development, as well as studies conducted in the interests of Swedish defence and the safety and security of society. The organisation employs approximately 1000 personnel of whom about 800 are scientists. This makes FOI Sweden's largest research institute. FOI gives its customers access to leading-edge expertise in a large number of fields such as security policy studies, defence and security related analyses, the assessment of various types of threat, systems for control and management of crises, protection against and management of hazardous substances, IT security and the potential offered by new sensors.

FOI
Defence Research Agency
Defence & Security, Systems and Technology
SE-164 90 Stockholm

Phone: +46 8 555 030 00
Fax: +46 8 555 031 00

www.foi.se

Literature Survey of Progressive Damage in Composite Bolted Joints

JOAKIM SCHÖN

NFFP-Projektet EFFEKT, Leverabel D3-1

FOI-R—3218--SE
ISSN 1650-1942

Technical report
June 2011

Defence & Security, Systems and Technology

Joakim Schön

Literature Survey of Progressive Damage in Composite Bolted Joints

NFFP-Projektet EFFEKT, Leverabel D3-1

Titel	Litteraturstudie av progressiv skadetillväxt i kompositförband med fästelement
Title	Literature Survey of Progressive Damage in Composite Bolted Joints
Rapportnr/Report no	FOI-R—3218--SE
Rapporttyp Report Type	Teknisk rapport Technical report
Sidor/Pages	16 p
Månad/Month	Juni/June
Utgivningsår/Year	2011
ISSN	ISSN 1650-1942
Kund/Customer	Vinnova/Saab
Projektnr/Project no	E28178
Godkänd av/Approved by	Maria Sjöblom

FOI, Totalförsvarets Forskningsinstitut

Avdelningen för Försvars- och säkerhetssystem

164 90 Stockholm

FOI, Swedish Defence Research Agency

Defence & Security, Systems and Technology

SE-164 90 Stockholm

Sammanfattning

Förband konstrueras oftast för att brott ska ske som hålkantskrossning, trots att det inte resulterar i ett optimalt förband. Brott med hålkantskrossning i ett förband sker genom att bulten krossar närliggande kompositen när bulten förskjuts parallellt med plattan. Det progressiva brott som sker omfördelar lasten i strukturen och i förbandet vilket gör att brottet kan stanna då andra bultar tar mer last. Brottprocessen är komplicerad med komposit som krossas vid hålkanten, chip out, matrissprickor, fiber brott, delaminering, kinking av 0^{o}-lamina, och stora skjuvsprickor. Att modellera alla de möjliga brott-moderna som ofta pågår simultant är väldigt svårt och istället använder man brottkriterier i varje FE-element. När brott predikteras reduceras elementets styvhet genast till i storleksordningen 10 % av dess ursprungliga värde. De fördelningar av element med brott i som rapporterats förutsäger inte de stora skjuvsprickor som observeras i experiment. Den modellerade last-förskjutningskurvan har sällan den horisontella delen vid maximal last som observeras experimentellt.

Nyckelord: Bultförband, Hålkantskrossning, Progressivt brott, Komposit

Summary

Joints are usually designed such that they fail in bearing mode, even though that does not result in an optimum joint. When joints fail in bearing mode the bolt is crushing the composite as the joint fails. The progressive failure redistributes load in the structure and joint such that progressive failure might stop due to other bolts taking more load. The failure process during bearing failure is complicated with crushing of hole surface, chip out, matrix cracking, fibre failure, delamination, kinking in 0^{o}-plies, and major shear cracks. To model all the different kinds of failure going on simultaneously is very difficult and instead different failure criteria are applied and the material properties of the elements are adjusted when failure is predicted. Usually the material properties are reduced instantaneously to 10% of their original value. The obtained damage patterns do not predict the large shear cracks observed in experiments. In most cases the modelled load-deflection curves do not have the experimentally observed horizontal part at maximum load.

Keywords: Bolted joint, Bearing failure, Progressive failure, Composite

Innehållsförteckning

1 Introduction

Bolted joints are used extensively in composite aircraft structures to join parts together. Joints are together with impact damage often the “problems” that drives the structural design. There are several failure modes for bolted joints, such as net section, shear out, pull through, tensile bolt failure, and bearing failure. Bearing failure is the only in-plane failure mode that is non-catastrophic. Therefore, joints are usually designed such that they will fail in bearing mode, even though that does not result in an optimum joint. When joints fail in bearing mode the bolt is crushing the composite as the joint fails. During this crushing process the bolt is still able to transfer approximately maximum load. The progressive failure redistributes load in the structure and joint, such that the progressive failure might stop due to load redistribution as other bolts end up taking more load. This makes it important to understand, and be able to model, the progressive failure. This literature review deals with progressive failure of bolted joints.

2 Experimental Studies

Nassar et al.[1] studied the failure of two bolts single lap joints with composite/composite plates and composite/aluminium plates. The composite was an epoxy/glass woven material. The damage was observed with an optical microscope. The M8 fasteners were either mounted finger tight or tightened to 16 Nm. The joint failed in net section and the fastener torque did not have any effect on the failure load. For the finger tight case significant delamination near the holes were observed. When the bolt was tightened beyond finger tight no significant delaminations was observed due to the presence of compressive stresses below the bolt head.

Choi et al.[2] have compared the strength of composite joints, with and without clamping force, and they found that applying a clamping force nearly doubled the joint strength.

Ireman et al.[3] have investigated development of damage in a composite single-lap joint. Figs. 1 and 2 show a cut through the bolt hole in the loading direction and at 45^{o} angle. A summary of the damage process is given in Fig. 3.

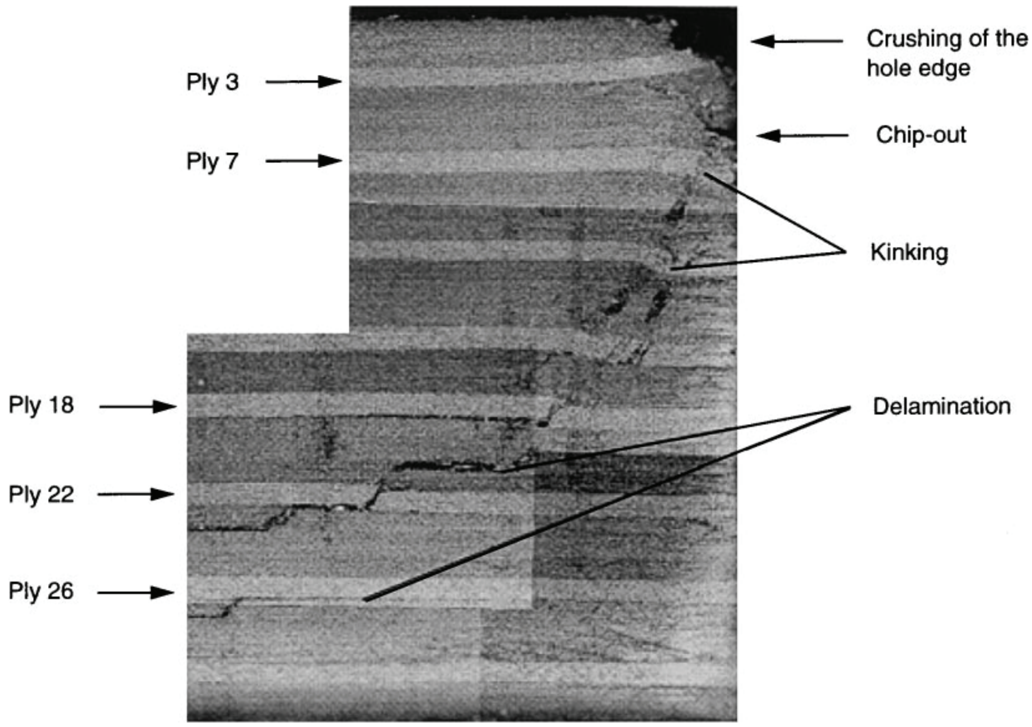

Fig. 1 Damage at failure along center line.

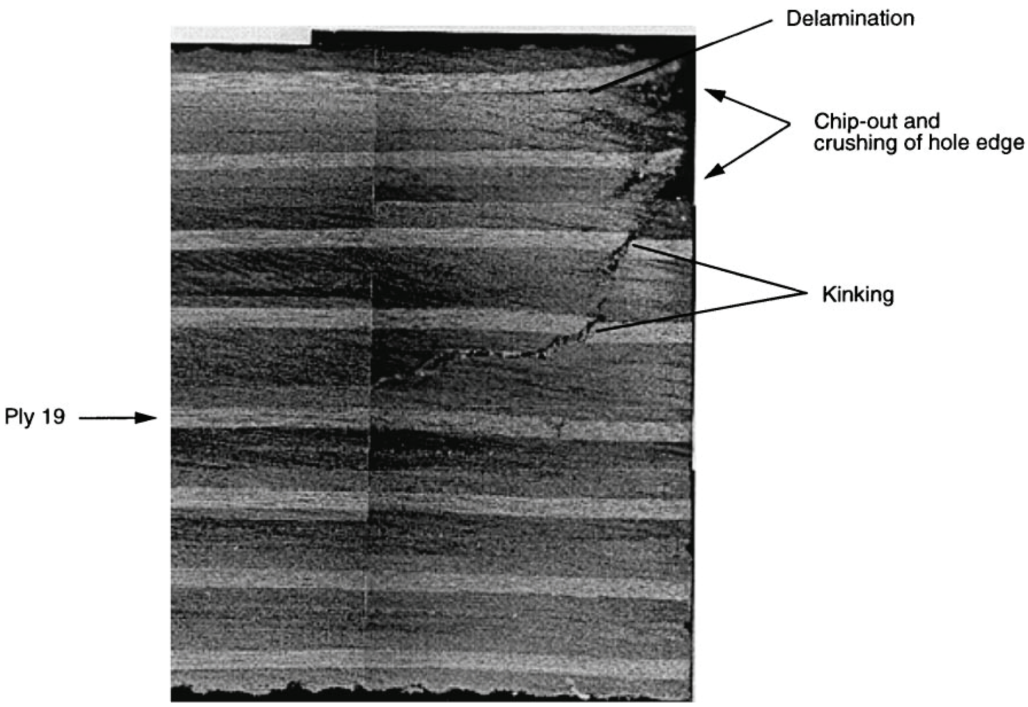

Fig. 2 Damage at failure along 45° line.

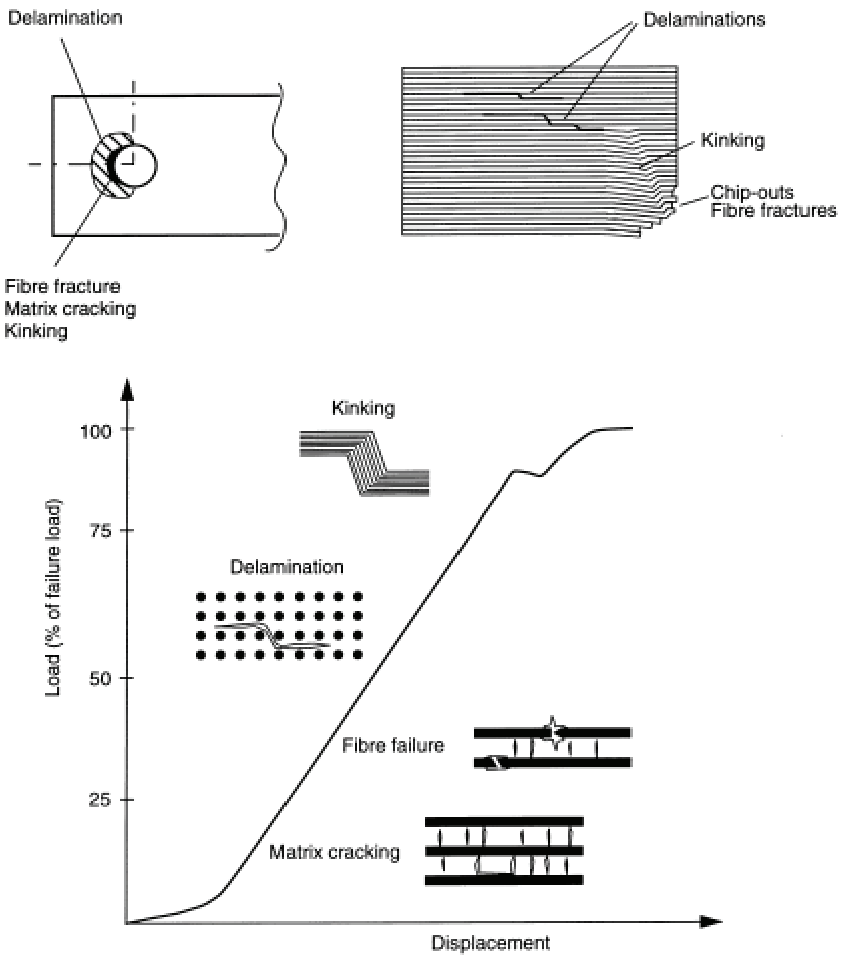

Fig. 3 Schematic illustration of failure process leading to joint failure.

Ekh et al.[4] have studied the development of bearing damage in three specimens loaded to different load levels, see Fig. 4. Severe damage has developed already at 23 kN which correspond to an average bearing stress of 920 MPa. Shear cracks through single laminas occur at several loacations and delamination between the outermost 0^o- and 90^o-plies has started. At 26 kN, the lamina shear cracks have merged into larger cracks that propagates from the center of the laminate towards the surfaces in approximately 45^o angle. Since the laminate surfaces are clamped by the aluminium plates (single fastener torqued with 6 Nm), the laminate is still capable of carrying an increasing load, which generates a second set of shear cracks that progresses from the centre to the surfaces of the laminate as shown. This stage-by-stage process is characteristic for clamped laminates. Kink band in a 0^o-ply is shown in Fig. 5.

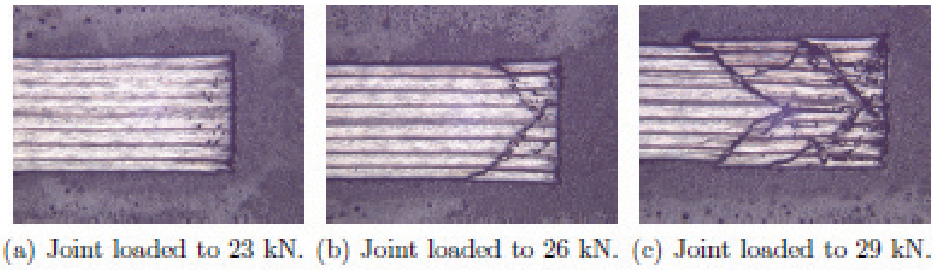

Fig. 4 Bearing damage in double lap specimens subjected to different levels of tension loading.

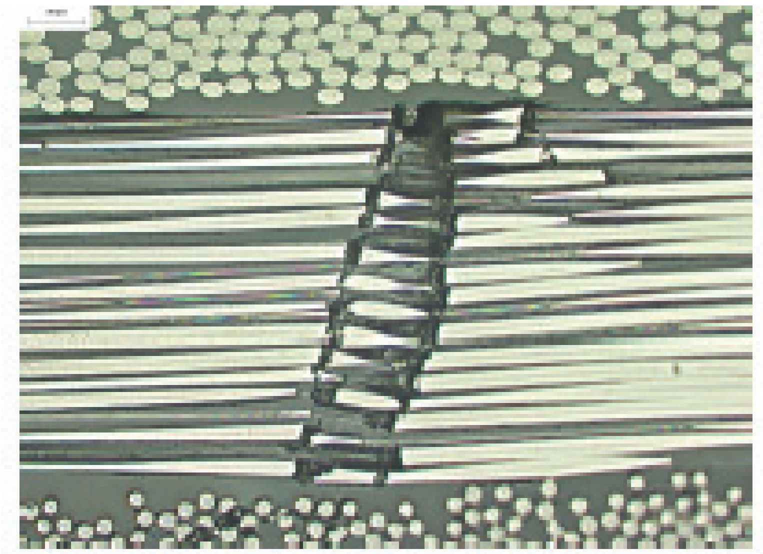

Fig. 5 Close-up of kink band in 0^o-ply

Wang et al.[5] have done a microstructure study of bearing damage. They studied both pin-loading and loading with bolt and washers. First they studied the pin-loading case and found that the bearing strength increased for specimens with a 90^o layer on the surface compared to specimens with a 0^o layer. The reason is that 0^o plies located on the laminate surfaces tend to fail by splitting and breaking away from the laminate under bearing loads. In a schematic description of pin-bearing damage the shear cracks are formed by the accumulated in-plane compression failure in each individual ply of the laminate and appear to be the primary failure mode of pin-bearing damage. It is believed that pin-bearing specimens fail catastrophically because damage in composites grows to a certain extent where shear cracks propagate and reach the free surfaces, or shear cracks merge and initiate unstable delamination growth. At this point, the laminates lost their integrity and were unable to carry higher bearing loads. Regardless of the ply orientation and the thickness of the laminate, the distance measured from the bearing contact surface to the location where the shear cracks merge, or where shear cracks reach a free surface, is about one quarter of the laminate thickness.

During bolt-bearing tests the clamping force was measured and first the clamping force grows almost linearly with the increase of applied load. Secondly, the clamping force increases nonlinearly in relation to the nonlinear load-deflection curve. This nonlinear response can be attributed to the accumulation of bearing damage. Finally, as the applied load nears the ultimate load level, at which point extensive bearing damage accumulates in the composites, the clamping force increases rapidly even though the applied load is kept nearly constant.

The mechanisms of bearing failure in bolted composite joints occurs stage-by-stage as damage propagates into the composites. Within each stage, a set of shear cracks will be formed for joints with low initial clamping pressure due to accumulated damage in individual plies of the laminate. Shear cracks may not be formed in joints with high initial clamping pressure due to the restraints of the transverse expansion of damaged material. However, the nature of the bearing failure mechanisms remains unchanged. The increase of bearing strength with the increase of clamping pressure can probably be attributed to friction forces.

At FFA a large number of experimental studies of composite joints were performed during the 80 ties.[6-21] The reports are listed here to make sure earlier works are not forgotten.

3 Numerical Studies

Tay et al.[22] have written an extensive literature review of progressive failure analysis in composites. They then apply an element-failure method (EFM) on several problems among which one is a rigid pin in a composite plate. The idea and assumption of the EFM is that the effects of damage on mechanical behaviour can be essentially described by the effective nodal forces of a finite element (FE). There are explicit relations between the nodal forces and the elastic stiffnesses of an FE. When an element fails, external nodal forces are applied iteratively, so that the net nodal forces of adjacent elements become zero eventually. Each iterative step involves applying the external nodal force of the same magnitude but opposite direction to the net internal nodal force due to adjacent elements. After each successive step, the net internal nodal force will decrease in magnitude until a very small value is left. This iterative process leaves the original (undamaged) material stiffness properties unchanged, and is thus computationally efficient since every step and iteration is simply an analysis with the updated set of applied nodal forces. For this reason, it may also be called the nodal force modification method. Hence, no reformulation of the FE stiffness matrix is necessary. When an element fails in matrix-dominated mode, nodal forces are modified in the transverse to fiber direction, but if fiber-dominated failure is predicted, the nodal forces are modified in both longitudinal and transverse directions. Applying the method to a pinloaded composite resulted in that the horizontal progressive damage region for bearing failure could not be well modelled.

Goswami[23] have modelled bearing strength and progressive failure of a pin-loaded composite. The model used 4-noded shell elements and a rigid pin. Three different failure criteria were used, Hashin’s criteria, Maximum stress failure criteria, and Tsa-Wu failure criterion. From the paper it is not clear how the element stiffness properties were degraded after failure. Strength was fairly well predicted whereas the progressive failure was not compared to experiments.

Kweon et al.[24] modelled progressive failure of a pin-loaded joint. Each layer was modelled with eight-node laminated shell elements and for failure they used three different failure criteria, Maximum stress criteria, Tsai-Wu criterion, and Yamada-Sun criterion. The numerical method to degrade the stiffness of the failed area is based on the complete unloading model. According to this model, the stress and stiffness components corresponding to the failure mode of each layer are assumed to be completely unloaded. The stiffness degradation method is well suited for brittle materials, such as carbon/epoxy composites, with negligible plastic deformation. This model also provides the most conservative estimate for the post-failure load-carrying capability of the structure under consideration. For most of the considered geometries the combined maximum stress (for fabric) and Yamada-Sun (for unidirectional plies) criteria accurately predicted the failure loads of the joints with a deviation of 4.7% to 23%.

Riccio[25] have studied progressive failure in single bolted joints. He used separate failure criteria for the failure modes matrix tensile failure, matrix compression failure, fiber tensile failure, fiber compression failure, and fiber-matrix shear out failure. For material property degradation he used a ply discount method, belonging to the instantaneous unloading category of material degradation models. At failure the elastic properties of the element was reduced to 10% of its original value according to the failure mode. For the composite/composite joint the progressive damage approach is able to follow the whole path of the experimental load-displacement curves, and also provides a good estimation of the final failure load (numerical failure load = 15.3 kN, average experimental failure load = 16.4 kN).

Goyal et al.[26] have studied progressive damage in a bearing loaded composite plate. At each load step all failure criteria used are applied at each Gaussian point. If failure occurs, the damage state is obtained and the components of the stiffness matrix are reduced as

$$\overline{C}_{ij} = C_{ij}\left(1 - D_i\right)\left(1 - D_j\right).$$

The components were reduced to a small value instead of zero, because a reduction to zero leads to numerical difficulties in the nonlinear procedure. The damage mode related to fiber failure, D_1, was chosen as $D_1 = 1 - \sqrt{E_{22}/E_{11}}$. If matrix-cracking occurs in tension, the damage D_2 is chosen as 0.9 and in compression is chosen as 0.7.

Choi et al.[2] have predicted the failure load of single bolt joints using the failure area index method. They were able to predict failure within 23% using Yamada-Sun and Tsai-Wu failure criteria.

McCarthy et al.[27] have studied progressive damage in a single lap joint with three bolts. The progressive damage model was implemented using the ABAQUS subroutine, USDFLD, which allows material properties to be a direct function of predefined field variables, which themselves can be a function of any material point (Gauss point) quantity such as stress, strain, temperature, etc. Hashins failure criteria was used to predict failure. Once the failure criteria were met, the field variables were updated and used to reduce the material properties to 10% of their original value. As a point has been detected to fail, it must remain in that condition and not 'heal' after the stresses redistribute. When material properties are degraded at a point, the load redistributes to other points, which could then fail themselves. It is therefore necessary to iterate at the same load level when material properties change to determine if other material points undergo failure. The models generally failed to provide a convergent solution all the way to ultimate failure, due to severe distortion of the damaged elements, so ultimate failure load predictions was not possible.

Freddie Gunbring did his master degree project at Saab modelling fastener flexibility using FEM.[28]

4 Summary and Conclusions

The failure process during bearing failure is complicated with crushing of the hole surface, chip out, matrix cracking, fibre failure, delamination, kinking in 0^{o}-plies, and major shear cracks. To model all the different kinds of failure mechanisms going on simultaneously is very difficult and instead different failure criteria are applied and the material properties of the elements are adjusted when failure is predicted locally. Usually the material properties are reduced instantaneously to 10% of their original value. The obtained damage patterns do not predict the large shear cracks observed in experiments. In most cases the modelled load-deflection curves do not have the experimentally observed horizontal part at maximum load.

5 References

1) Nassar, S. A., Virupaksha, V. L., Ganeshmurthy, S., (2007), Effect of Bolt Tightness on the Behavior of Composite Joints, *J. Pressure Vessel Technology*, Vol. 129, pp. 43-51.

2) Choi, J.H., Ban, C.S., and Kweon, J.H., (2008), Failure Load Prediction of a Mechanically Fastened Composite Joint Subjected to a Clamping Force, *J. Composite Materials*, Vol. 42, pp. 1415-1429.

3) Ireman, T., Ranvik, T., Eriksson, I., (2000) On damage development in mechanically fastened composite laminates, *Composite Structures*, Vol. 49, pp. 151-171.

4) Ekh, J., Zenkert, D., Schön, J.Prediction of Bearing failure in Composite Single-lap Joints, Paper E, Doctoral Thesis in Lightweight Structures, Stockholm, Sweden 2006, Multi-Fastener Single-lap Joints in Composite Structures, Johan Ekh.

5) Wang, H.-S., Hung, C.-L., Chang, F.-K., (1996), Bearing Failure of Bplted Composite Joints. Part I: Experimental Characterization, J. Composite Materials, Vol. 30, pp. 1284-1313.

6) Larsson, N., Håltryckshållfastheten hos glasfiberarmerad polyester SAAB-SCANIA 5515-1, 1973, FFA HU-1520

7) Gillberg, R., BESTÄMNING AV TILLÅTEN BROTTLAST I ENSKÄRIGA SKRUVFÖRBAND MED SEXKANTSKRUV I KOLFIBERLAMINAT, 1978, FFA HU-1981

8) Larsson, N., UTMATTNINGSHÅLLFASTHET HOS ETT SKJUVBELASTAT SKRUVFÖRBAND I KOLFIBERLAMINAT, 1979, FFA HU-1982

9) Gillberg, R., UTPROVNING AV LÄMPLIGT BLINDELEMENT FÖR ANVÄNDNING I FÖRBAND MED KOLFIBERLAMINAT, 1978, FFA HU-1985

10) Larsson, N., BESTÄMNING AV BROTTLAST HOS SKJUVBELASTADE FÖRBAND AV KOLFIBERARME- RAD PLAST, 1982, FFA TN 1982-05

11) Palmberg, B., Experimentell bestämning av brottlaster hos enskäriga skjuvbultför-band i grafit/epoxy, 1983, FFA TN 1983-09

12) Magnusson, Å. Kompletterande provning med skruvförband av kolfiberarmerad plast.¤Verkstadsavvikelser och dubbel avskärning, 1983, FFA TN 1983-12

13) Ericsson, P., Dragbelastade skruvförband i Al-KAP med liten delning, 1983, FFA TN 1983-26

14) Ericsson, P., Blom, A., Provning av skjuvbelastade skruvförband i KAP:Theta-faktorn, 1984, FFA TN 1984-18

15) Areschoug, T., Provning av skjuvbelastade skruvförband i kolfiberlaminerad plast, inverkan av försänkningsdjup, 1984, FFA TN 1984-24

16) Areschoug, T., Provning i tvåradiga skjuvförband i kolfiberarmerad plast, 1984, FFA TN 1984-26

17) Palmberg, B., Bultflexibilitet för titanskruvar i förband av stål och kolfiberar- merad plast, 1984, FFA TN 1984-55

18) Nilsson, S., Experimentell undersökning av livslängden hos spektrumutmattade skruvförband med skarvplattor av KAP-KAP, KAP-Al och Al-Al, 1984, FFA TN 1984-65

19) Nilsson, S., Experimentell studie av skjuvhållfastheten i skruvförband innehållande skarvplattor av kap med fibrer av IM-typ, 1985, FFA TN 1985-25

20) Carlsson, L., Sindelar, P., Nilsson, S., Avtagande av ändeffekter iSkruvförband av grafit/epoxy, 1985, FFA TN 1985-34

21) Nilsson, S., Studie av förspänningskraftens temperaturberoende och dess inverkan på utmattningsegenskaperna hos skruvförband i KAP, 1987, FFA TN 1987-72

22) Tay, T. E., Liu, G., Tan, V. B. C., Sun, X. S., and Pham, D. C., (2008) Progressive Failure Analysis of Composites, *J. Composite Materials*, Vol. 42, No. 18, pp. 1921-1966.

23) Goswami, S., (2005), A Finite Element Investigation on Progressive Fasilure Analysis of Composite Bolted Joints Under Thermal Environment, *J. Reinforced Plastics and Composites*, Vol. 24, No. 2, pp. 161-171.

24) Kweon, J., H., Shin, S., Y., and Choi, J., H., (2007) A Two-dimensional Progressive Failure Analysis of Pinned Joints in Unidirectional-Fabric Laminated Composites, *J. Composite Materials*, Vol. 41, pp. 2083-2104.

25) Riccio, A., (2005) Effects of Geometrical and Material Features on Damage Onset and Propagation in Single-lap Bolted Composite Joints under Tensile Load: Part II – Numerical Studies, *J. Composite Materials*, Vol. 39, pp. 2091-2112.

26) Goyal, V., K., Rome, J., I., Klug, J. C., Chang, D., J., Katzman, H. A., and Ross, F., D., (2006) Failure Modeling and Simulation of Composites Subjected to Bypass and Bearing Loads, *AIAA* 2006-2172.

27) McCarthy, C. T., McCarthy, M. A., Lawlor, V., P., (2005) Progressive damage analysis of multi-bolt composite joints with variable bolt-hole clearances, *Composites: Part B*, Vol. 36, pp. 290-305.

28) Gunbring, F., Prediction and Modelling of Fastener Flexibility Using FE, Degree Project, Dept. of Management and Engineering, Linköping University, LIU-IEI-TEK-A—08/00368—SE, SAAB-DES-R-002