2010-36-0154I

Design and analysis of aeronautical repair: fastened x bonded

Ribeiro, M. L., Barbosa, A. A. F., Di Salvo, F., Borges, E. N., Basile, T. F., Tita, V.
Department of Materials, Aeronautical and Automobilist Engineering - Engineering School of São Carlos,
University of São Paulo, São Carlos, SP, Brazil

ABSTRACT

During the normal aircraft operation, some structural damages might occur due to, for example, bird strike or fatigue cracks. In order to keep the aircraft airworthiness, these damages could be repaired by bonded or fastened patches setting a new load path relieving the damaged structure. Bonded patches presents some advantages when compared with fastened ones, featuring better fatigue endurance and better finishing. The present work presents a study of advantages of bonded repair when compared to fastened repair, using a finite element analysis in order to model both type of structural repair. Thus, it is showed the repaired structure load redistribution, as well as, the nearby damage stress field modifications. Besides, the bonded repair is evaluated by a specific software for bonded join analysis (SAJ) developed by Aeronautical Structural Group of São Carlos Engineering School.

INTRODUCTION

In normal aircraft operations are not unusual find cracks in the aircraft structure, due to any incident or structural fatigue. In order to keep the aircraft airworthiness, these damages must be repaired, replacing the damaged part. Nevertheless, sometimes, it is not possible to remove the damaged part and a patch is used in order to set a new load path, decreasing the stresses in the crack tip, but increasing the structural weight. However, a lighter repair can be achieving by patches manufactured with composite materials.

One way to assembly these structural repair consist on using bonded joints which shows some advantages like a better fatigue endurance, joining dissimilar materials, better insulation, smooth surface and lighter weight. Nevertheless, there is no possibility to disassembly the joints. In order to minimize peeling stress should, the preparation of the surfaces, that will be bonded, must be done carefully to receive the adhesive, which may be degraded by the environment (Mortensen [1]). On the other side, the fastened joints could be disassembled, there are no special needs of superficial preparation which allow performing these repair in any maintenance center. However, the structural weight can increase due to fasteners and there are more stress concentration points due the holes.

Once crack is detected and it is not suitable to replace the part, the crack can be removed by cutting the crack region, smoothing the edges and reducing the stress concentration in the crack tip. After this operation, the part can be repaired using fastened or bonded patch.

Many researches have been carried out about bonded joints, trying to predict the behavior, failure, and the strength of bonded joints using finite element models, analytical models or experimental tests. Thomsen [2] showed that the multi-directional adhesive state of stress could be related to a unidirectional state of stress through a function similar that presented by von Mises. Mortensen [1], in his PhD thesis, presented a development of a computational tool for analysis of bonded joints showing the equations and hypothesis for various types of bonded joints, as well as, the solving process of differential equations using the multi-segment method of integration. Ganesh and Choo [3] showed the effect of spatial grading of adherent elastic modulus on the peak stress and stress distribution in the single lap joint, which lead to decrease in the stress peak and a more uniform shear stress distribution.

Belhouari, Bouiadjra, and Kaddouri [4] showed a comparison between single and double lap joint using a finite element model. In this study, the researchers showed the advantages of using a symmetric composite patch for repairing crack. Also, that double patch has lower stress when compared with single patch repair. Agnieszka [5] showed a numerical method, regarding the sensitivity for hydrostatic stress, for prediction of the delamination initiation, which allows simulating the failure of the joint and composite substrate.

Regarding the fastened joints design, some aspects should be observed, for example, fastener edge distance, pitch, the number of fastener in a row, the fastener stiffness compared with the patch and the structure. It is important to notice that the fastener edge and pitch distance are different for metallic and composite parts. Also, the stiffness ratio between fasteners and the other parts act on the fastener load distribution, so, Niu [6] showed an analytical model for obtain the load in each fastener of a row.

More recently, the researchers Ekh and Schön [7] conducted an study using finite element analysis to model a multi-fastener, single-lap, composite-to-aluminum joint showing the effects of the overlap length, the effect of the stiffness mismatch in the plates on the load distribution and the effect of the fastener stiffness.

In order to show the differences between fastened and bonded repair, the present work shows the linear elastic response of an aluminum plate with a hole showing the differences in the stress distribution in the crack surrounded area for unrepaired plate and repaired plate (bonded and fastened), as well as the change in the plate stiffness and weight of repaired structure. The commercial software ABAQUS*TM* was used for numerical simulations. Regarding the adhesive bonded repair, the stresses in the adhesive layer are obtained using the software SAJ (System of Analysis of Joints) developed by Aeronautical Structural Group of São Carlos Engineering School.

FINITE ELEMENT MODEL

To proceed with this study, each component of bonded and fastened repair are modeled using a commercial finite element code ABAQUS TM.

DAMAGED PLATE

Regarding the procedure of cutting the crack affected area, smoothing the edges, the damaged aluminum plate and the hole have the following dimensions: 250mm x 120mm x 1.07mm for plate and 22mm and 2mm of radius for the hole. These dimensions are shown in Figure 1.

The finite element model for the plate uses the 20 nodes tetrahedron elements (Figure 2), named C3D20 (ABAQUS - User´s manual [8]).

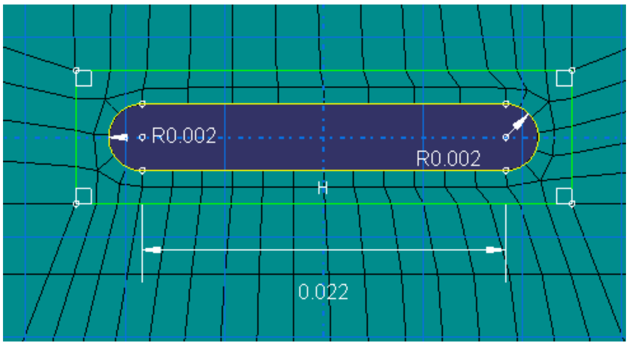


Figure 1: Hole dimensions

The plate is clamped in one edge and in the opposite edge is applied 0.25mm of prescribed displacement

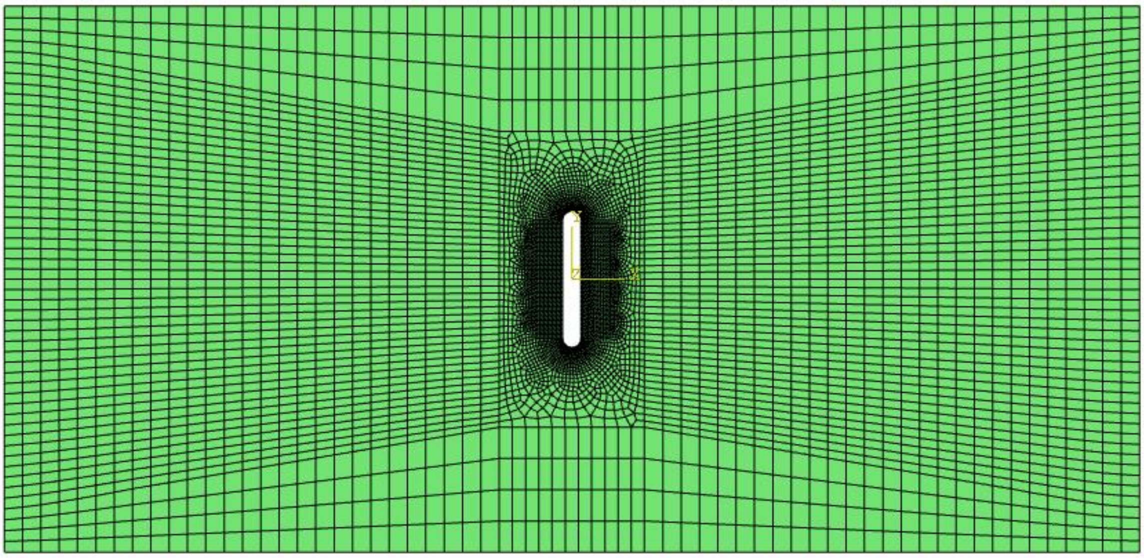


Figure 2: Plate Mesh.

The plate mechanical properties are shown in Table 1.

Table 1: Plate mechanical properties.

Material	E (GPa)	Poisson
Plate – Al 7475	72	0.33

The boundary conditions applied are clamped one edge and imposes a prescribed displacement of 0.25mm in the opposite edge.

BONDED REPAIR

Regarding the bonded repair, the patch is considered manufactured using unidirectional, prepreg M10, composite material (Tita [9]) for each layer; see Table 2 for mechanical properties. The composite patch dimensions are 70mm x 40mm and the layup are $[0/90]_{10}$. Each layer is 0.18mm thick.

The patch finite element model use an 8-node, quadrilateral, first-order interpolation element with reduced integration, named SC8R (ABAQUS - User´s manual [8]). Also, Hashin [10] failure criteria is used, Table 3 presents the strength limits.

Table 2: Patch mechanical properties (Tita [9])

	E_{11} (GPa)	E_{22}=E_{33}(GPa)	G_{12}=G_{13}(GPa)	G_{23}(GPa)	ν_{12}=ν_{13}	ν_{23}
PrePreg M10	100	10	5.4	3.05	0.34	0.306

Table 3: Unidirectional layer strength limits - prepreg M10 (Tita [9]).

	X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S_{12}=S_{13} (MPa)	S_{23} (MPa)
PrePreg M10	1400	930	47	130	53	89

The epoxy adhesive is modeled as isotropic and linear-elastic behavior. Table 4 shows the adhesive mechanical properties. The adhesive layer is modeled using 8-node, first-order interpolation tetrahedron element, named C3D8 (ABAQUS - User´s manual [8]). The adhesive is 0.5mm thick.

Table 4: Adhesive mechanical properties.

Material	E (GPa)	Poisson
Epoxy adhesive	1.49	0.35

Figure 3 shows the bonded repair finite element model. Regarding the boundary conditions, the plate is clamped in one edge and a prescribed displacement of 0.25mm is applied in opposite edge. The interaction between adhesive layer and plates is modeled using the surface-to-surface formulation, described as "tie" at ABAQUS - User´s manual [8]. The adhesive layer dimensions are the same as was used for the composite patch.

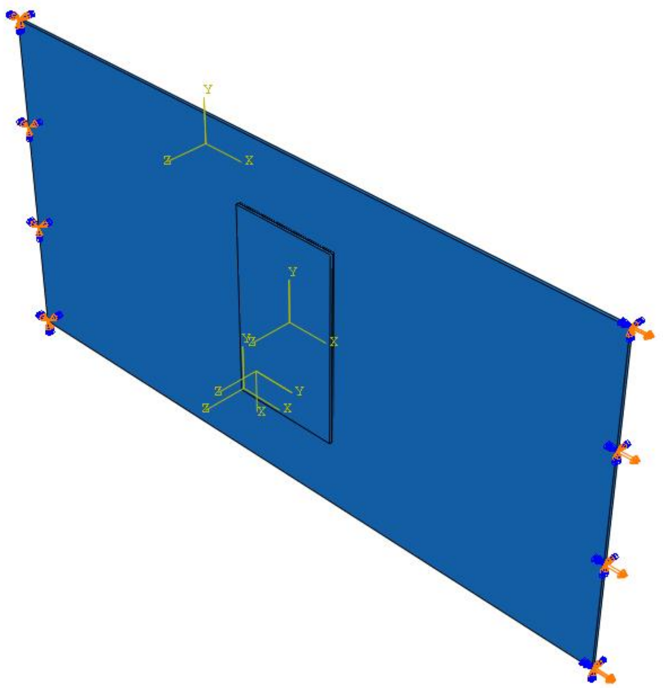
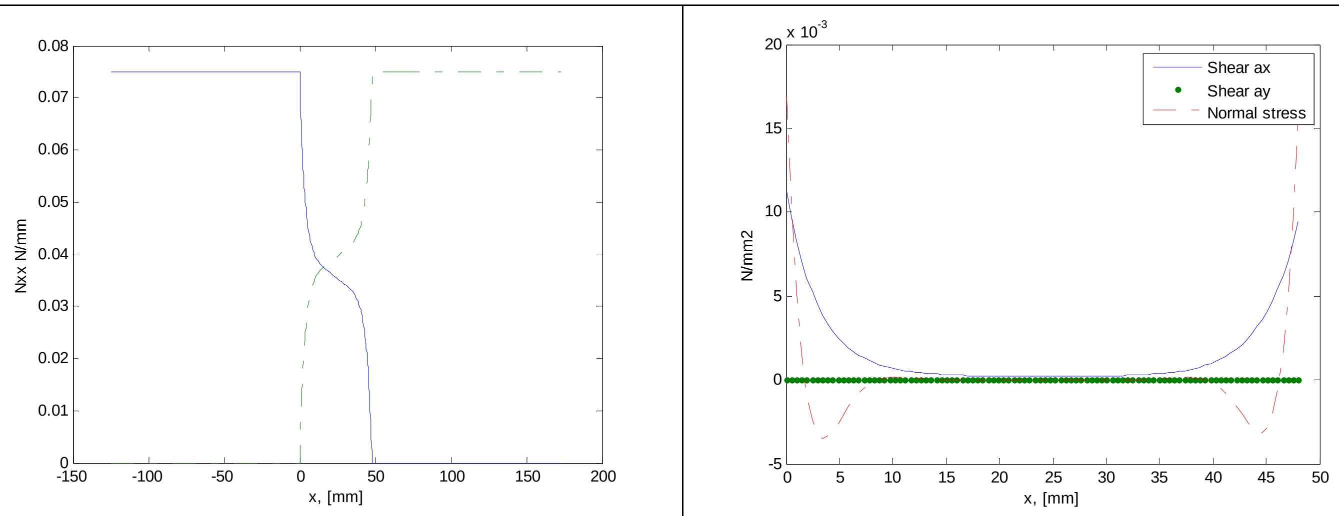


Figure 3: Model assembly and boundary conditions.

Computational toll (SAJ)

A computational tool, called SAJ, was developed in order to help the analysis of single and double lap bonded joints. This software was programmed in Matlab^{TM} language. In the case of composite adherents, this software is also capable to obtain the stress and strain for each layer. SAJ is also capable to solve composite/composite and metal/composite bonded joints (Ribeiro [11]). This software was used to design the bonded repair and verify the stresses distribution in the adhesive layer and the load transfer (Figure 4).



(a) (b)

Figure 4: (a) Load transfer; (b) Adhesive layer stress distribution

As were showed in Figure 4(b), the maximum value of the stress state, in the adhesive edges, does not cause adhesive plasticity, using maximum distortion energy (Misses) criteria, with yield stress σ_0 equal 20 MPa , which confirms the linear-elastic hypothesis for the structure behavior. Also, the patch does not fail under these load level, regarding first ply failure. Also, Figure 4 (a) shows a continuous load transfer between joint components.

FASTENED REPAIR

In order to simulate the fastened repair, the plate was modified adding the holes for each fastener. The fastener diameter is 4.0mm. It is important to note that the minimum pitch and the edge distance is 12.0mm, about three times the fastener diameter.

The composite patch dimensions are 96mm x 76mm and the layup are $[0/90]_{10}$. Each layer is 0.18mm thick. Also, the same distances between holes and edges are kept for the patch. The patch finite element model use an 8-node, quadrilateral, first-order interpolation element with reduced integration, named SC8R (ABAQUS - User´s manual [8]). Furthermore, Hashin failure criteria is used in the composite patch. Table 2 shows the mechanical properties for composite unidirectional layer, and table 3 shows the strength limits.

The fasteners are modeled using 8-node, first-order interpolation tetrahedron element, see Figure 5, named C3D8 (ABAQUS - User´s manual [8]). Table 5 shows the mechanical properties for fastener.

Table 5: Fastener mechanical properties.

Material	E (GPa)	Poisson
Titanium	112	0.34

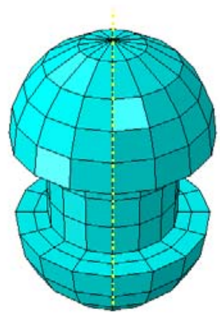


Figure 5: Fastener mesh.

Figure 6 shows the fastened repair finite element model. Regarding the boundary conditions, the plate is clamped in one edge and a prescribed displacement of 0.25mm is applied in opposite edge. The interaction between fasteners and plates is modeled using the surface-to-surface formulation described as "tie"at ABAQUS - User´s manual [8].

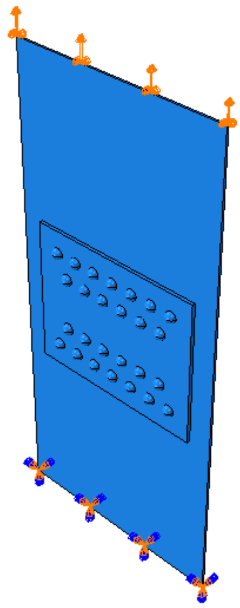


Figure 6: Model assembly and boundary conditions.

Concerning the galvanic corrosion between carbon fiber composite and aluminum plate, this problem can be solved by the use of films which involves the patch.

RESULTS

Simulations of unrepaired and repaired plate were performed.

Figure 7 presents the stress field (von Mises) for unrepaired plate (a), bonded (b) and fastened (7) repair. This figure shows how the repair act on the stress field near the plate cut. The biggest change in the stress field pattern happened for fastened joint. Even the bonded repair does not show a considerable change in the stress pattern, the bonded repair presents the biggest reduction in the maximum stress value.

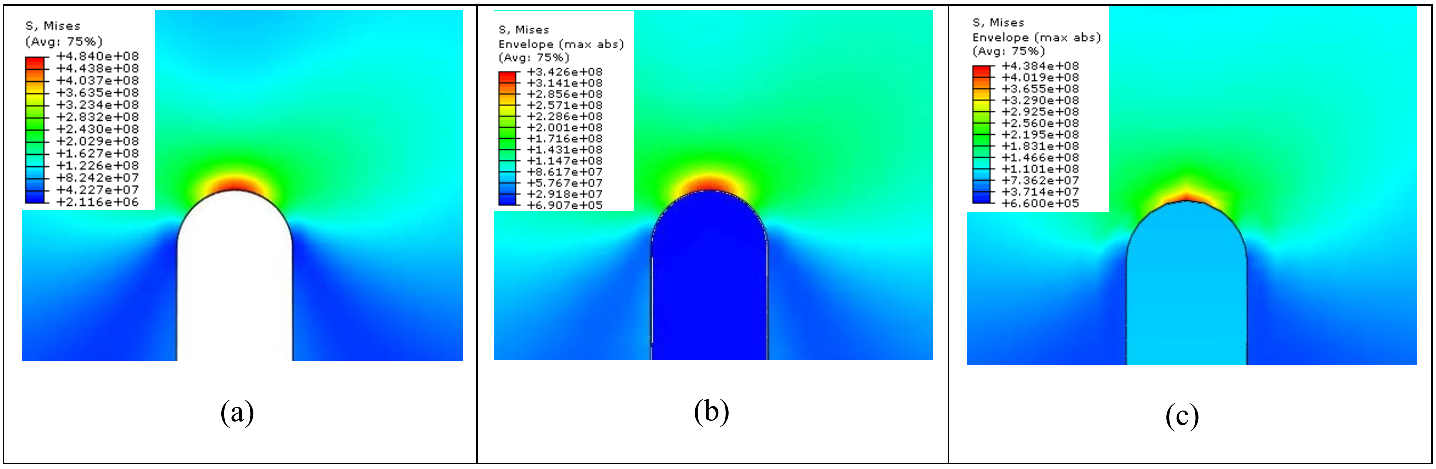


Figure 7: Stress field for unrepaired plate (a), bonded repair (b) and fastened repair (c).

Figure 8 presents force x displacement curve for the unrepaired and repaired plate. The maximum force values achieved for a prescribed displacement of 0.25mm are: 8887.12 N, 9019.01N and 9549.17N for unrepaired plate, bonded and fastened repaired plates respectively.

As were showed, the fastened repair is stiffer than bonded repair despite the operation of drilling holes for fastener installation, but the patch used for the fastened repair, due to minimum distances between edges and fasteners, is bigger than the bonded patch.

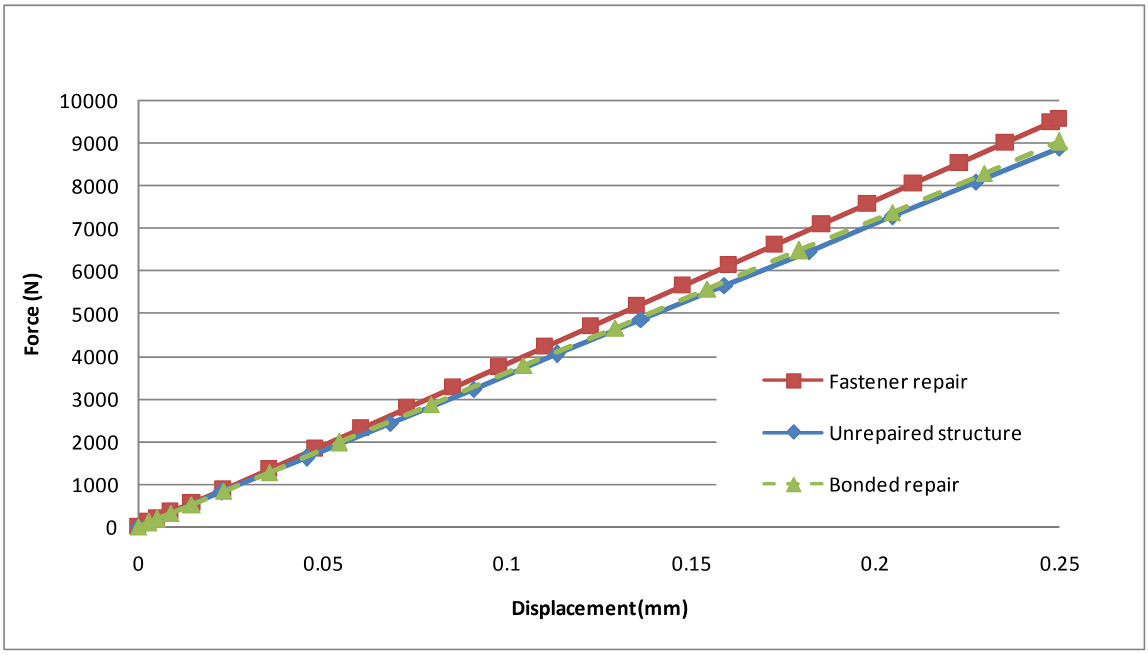


Figure 8: Force x Displacement

Another remarkable point is the reduction of the stress concentration factor in the repaired structures, see Table 6. The stress concentration decreases 18.3% for fastened repair and 31.9% for bonded repair.

Table 6: Stress concentration (Kt) for unrepaired, fastened and bonded repair.

	Kt - unrepaired plate	Kt - repaired plate	Difference - %
Fastened repair	7.27	5.94	18.3
Bonded repair	7.27	4.95	31.9

SUMMARY AND CONCLUSIONS

Despite the small difference in the structural stiffness when compared with unrepaired structure, the repaired structure are stiffer as well as, the value of the maximum stress is lower for the repaired structure. The fastened repair is stiffer than bonded repair due to differences in the patch size.

Another important conclusion regards the decreasing of stress concentration near the stress concentration point, this reduction is more evident for bonded repair mostly due to a better load transfer in bonded joints.

Finally, both kind of repair are suitable achieve a reasonable performance. A bonded repair possess a better load transfer between parts, which increases the reduction in the stress concentration factor improving the fatigue life of the damaged part, nevertheless the bonded repair demands a good superficial treatment before bonding process.

REFERENCES

1. Mortensen, F., 1998, "Development of Tools for Engineering Analysis and Design of High-Performance FRP-Composite Structural Elements", PhD Thesis, Institute of Mechanical Engineering, Aalborg University, Aalborg.
2. Thomsen,O. T., 1992, "Elasto-Static and Elasto-Plastic Stress Analysis of Adhesive Bonded Tubular Lap Joints", Composite Structures, Vol. 21, pp. 249-259.
3. Ganesh, V. K., Choo, T. S., 2002,"Modulus Graded Composite Adherents for Single Lap Bonded Joints", Journal of Composite Materials, Vol.36, pp.1757-1767.
4. Belhouari, M., Bouiadjra, B. B. and Kaddouri, K., 2004, "Comparison of Double and Single Bonded Repairs to Symmetric Composite Structures: A Numerical Analysis", Composite Structures, Vol.65, pp. 47-53.
5. Agnieszka, D., 2009, "Prediction of the Failure Metal-Composite Bonded Joints", Computational Materials Science, Vol.45, pp.735-738.
6. NIU, M.; CHUN, Y. (1989). Airframe structural design – Practical design information and data on aircrafts structures. Burbank: Lockheed Aeronautical System Company.
7. Ekh, J., Schon, J., 2007, "Finite element modeling and optimization of load transfer in multi-fastener joints using structural elements", Composite Structures, Vol. 82, pp. 245-256
8. ABAQUS 6.6, 2006 "User´s manual", Dassualt Systèmes.
9. TITA, V. (2003). Contribuição ao estudo de danos e falhas progressivas em estruturas de material compósito polimérico. Tese (doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2003.
10. Hashin, Z., 1980,"Failure Criteria for Unidirectional Fiber Composites", Journal of Applied Mechanics, vol.47, pp.329-334.
11. Ribeiro M. L., 2009, "Programa para Análise de Juntas Coladas: Compósito/Compósito e Metal/Compósito.", Master thesis, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos (in Portuguese).

CONTACT INFORMATION

Marcelo Leite Ribeiro: strova@hotmail.com

ACKNOWLEDGMENTS

The authors are grateful for the financial support from CAPES and Prof. Reginaldo Teixeira Coelho for the ABAQUS^{TM} license.