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DESIGN IMPROVEMENT OF HYBRID COMPOSITE JOINTS BY AXIOMATIC DESIGN

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ABSTRACT

The performance of a hybrid (bolted/bonded) joint depends on many parameters and its design becomes complex when the design aims to create a synergy between these two joining methods which are commonly used for composite plates. In this paper, Axiomatic Design is applied to analyze the parameters that influence the load transfer between the different components of the joint as well as the maximum stress in the adhesive. A first decomposition of the joint into functional requirements and design parameters leads to a coupled design. A decoupled design is obtained through the reordering and reformulation of both functional requirements and design parameters. The design matrix is then used to propose a new design through physical integration of the design parameters. Comparison between this new design and baseline geometry shows a reduction in the maximal stress concentration inside the joint. This improvement should result in higher load transfer capability while maintaining similar dimensions.

Keywords: hybrid composite joint, bonded, bolted, Axiomatic Design, design decomposition.

1 INTRODUCTION

Nowadays, aircraft design tends towards a more extensive use of composite materials as a high strength to weight ratio directly impacts the desired performance. However, the joining of parts made of composite materials is a complex matter. Drilling holes for bolts or rivets in fibrous materials can lead to delamination or reduced strength. The addition of mechanical fasteners can also significantly increase the weight of a structure. This is partially why bonding of composite materials has become very popular. Bonded joints offer higher strength to mass ratios as well as higher static and fatigue strength than other joining methods [Chan, 2001]. However, in an attempt to further improve the performance of bonded joints as well as for aeronautical certification purposes, research on the combination of bonded joints with bolts or rivets, called hybrid joints, has become of major interest.

In this paper, an analysis of the couplings between the different design parameters of a hybrid joint is performed through an Axiomatic Design procedure. In section 1, a background on the performance of hybrid joints is presented according to a literature review. Then, in section 2, an Axiomatic Design decomposition is used to evaluate the different functional requirements and design parameters involved in the design of a hybrid joint. This work also presents the steps required to remove unnecessary coupling inside the design matrix. Section 3 presents a new design obtained through physical integration based on the decoupled matrix from section 2. Finally, in section 4, the new design is analysed and compared to the initial geometry in order to validate the results.

2 LITERATURE REVIEW

2.1 STRENGTH AND LOAD TRANSFER IN HYBRID JOINTS

When designing a mixed technology of joining, one of the goals is to benefit from the strengths of each joining method or simply to improve the performance of the first one by adding additional joining methods. The distribution of the loading within the joint is one of the main issues the research emphasises. Thus, one of the most important studies was performed by Hart-Smith [1985] who conducted an analytical study of the performance of a bonded/bolted composite to titanium stepped lap-joint. Using a high rigidity adhesive, the author predicted that the adhesive would transfer up to 98% of the external load. When using a low rigidity adhesive, Kelly [2006] showed that, in a single bolt single-lap hybrid joint, the bolt could transfer up to 32% of the external load. With similar results, Kweon *et al.* [2006] concluded that, for low strength adhesive, the addition of bolts greatly increases the strength of the joint while, for high strength adhesive, it is almost without results.

In the case of high rigidity adhesive, the bolts start transferring load only after the initial failure of the adhesive, thus helping to slow down the crack propagation [Hart-Smith, 1985]. This mechanism confers higher rigidity of hybrid joints at high external loads as well as improved fatigue life compared to bonded joints [Kelly, 2005; 2006]. Moreover, the addition of bolts in a bonded joint can also ensure structural integrity even after complete adhesive failure [Sawa *et al.,* 1989].

Many authors [Bois *et al.*, 2011; Oterkus *et al.*, 2007; Paroissien *et al.*, 2006; 2007] worked on promising analytical models to predict the stress distribution and the load transfer distribution in the joint. However, the use of linear material properties in the definition of these models reduces their usefulness without systematic comparison with test results or finite element analysis results.

Kumar *et al.* [2010] proposed an innovative new single lap hybrid joint configuration by adding bonded aluminum specimens in the overlap. These specimens served as additional load paths. The author obtained a 60% increase in the specific strength (load/mass) of these new joints compared to bonded joints.

2.2 FAILURE MECHANISMS OF HYBRID JOINTS

Another major issue influencing the design choices of a composite hybrid joint is its specific failure mechanisms. When in-plane loading occurs in a single-lap hybrid joint, one may isolate the different types of generated stress shown in Figure 1. For this type of joint, the load paths in both flat plates are not in the same plane. This offset of the load paths introduces a secondary bending of the adherents. This secondary bending generates peel stress in the adhesive layer, which is maximal near the edge of the overlap [Kelly, 2005]. The external load also generates shear stress which is the principal load transfer mechanism of the adhesive layer. Finally, bearing stress develops as the contact between the bolts and the adherents occurs.

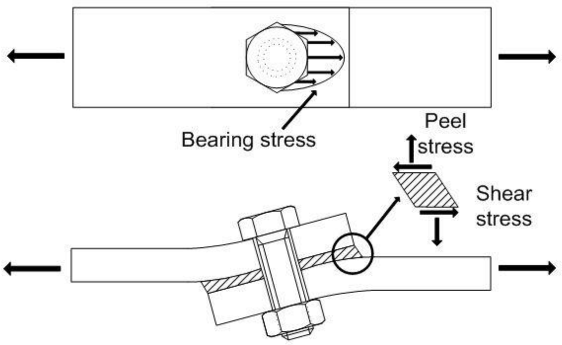

Figure 1. Principal stress in a single-lap hybrid joint.

In most single-lap hybrid joints, failure follows as a result of crack initiation in the adhesive layer due to high peel stress at the edge of the overlap [Kelly, 2006]. Therefore, reducing the maximal peel stress is an important goal in hybrid joint design. Stewart [1997] has shown that the joint strength can be increased by changing the stacking sequence in composite laminates. By placing the 0 degree ply closer to the adhesive, the joint static strength can be improved due to the increased bending stiffness of the adherents. Tapered edges can also increase the joint strength by lowering the free-edge interlaminar stresses in the adherents [Lin and Jen, 1999].

Fu and Mallick [2001] also found how bolt pretension can help to increase the static strength as well as fatigue performance in structural reaction injection molded (SRIM) composites. In their experiments, the authors showed that the addition of bolt pretension served to apply a compressive force in the adhesive layer. This compressive force has proven effective in reducing or even stopping crack propagation in the adhesive. However, the bolt pretension proved effective in delaying crack initiation only if the pretention was applied with the use of thick washers covering the entire overlap region.

Chan [2001] evaluated the stress concentration in hybrid composite joints. The author concluded that stress concentration is reduced in hybrid joints compared to bolted joints. Also, hybrid joints showed very low compressive bearing stress. It is suggested that joint failure by bearing stress is unlikely.

Lees and Makarov [2004] investigated the possibility to combine a mechanical system with a bonded system to obtain a more efficient joint than each separate system for use in piping. A right configuration of pin/bonded joint makes certain the joint failed outside of its overlap. They also noticed higher elongation at failure than for bonded or mechanically fastened joints alone.

3 DESIGN OF HYBRID JOINTS USING AXIOMATIC DESIGN

3.1 PROBLEM DEFINITION

The following section will identify the functional requirements and design parameters [Suh, 1990; 2001] involved in the design of a hybrid joint. Once an uncoupled design matrix is obtained, physical integration will be used to propose a new design. To validate the results, a comparison of the new design with a traditional geometry is performed. To achieve this, the coupling in a single lap hybrid joint will be analysed. This particular joint geometry has been chosen due to the high amount of available research. The initial problem can then be stated at the top level of functional requirement and design parameter as follows:

FR_0 = Join two flat plates in composite materials
DP_0 = Single lap hybrid joint

3.2 FIRST LEVEL OF DECOMPOSITION

The main goal of this research is to improve the performances of the joint by effectively using the advantages of both joining methods in the same joint. By doing so, the maximal load that can be transferred should increase. To achieve this, the functional requirements will mostly concern load transfer and failure mechanisms. The first level of functional requirements is then defined as:

FR_1 = Maximize the bolt load transfer capacity
FR_2 = Delay adhesive failure (crack initiation and propagation)
FR_3 = Minimize the secondary bending
FR_4 = Uniformly distribute the load inside the joint

Based on the literature review presented in section 2, the corresponding design parameters are:

DP_1 = Contact between the bolts shank and the flat plate holes
DP_2 = Clamping force (compression stress)
DP_3 = Bending stiffness of flat plates
DP_4 = In-plane rigidity of the joint

The design matrix obtained after the first level of decomposition is shown in Figure 3. At this stage in the FR-DP decomposition of this problem, no coupling is apparent.

	DP_1	DP_2	DP_3	DP_4
FR_1	X	0	0	0
FR_2	0	X	0	0
FR_3	0	0	X	0
FR_4	0	0	0	X

Figure 3. FR-DP matrix of first level decomposition.

3.3 SECOND LEVEL OF DECOMPOSITION

The second level of decomposition is obtained through the zigzagging process [Suh, 2001]. Each child must be defined based on its parent FR and its corresponding DP. For each FR, two children must be defined. Their definition is based on the knowledge that bolt load transfer in a hybrid joint is mostly the result of the contact between the shank and the flat plates, which generates bearing stress. McCarthy [2005] also showed that if there is a bolt-hole clearance in a bolted joint, the bolts start transferring load only once the relative displacement between the flat plates is high enough to bring the bolt shank into contact. Based on these observations, the second level of functional requirements for FR_1 can be defined as:

$FR_{1.1}$ = Maximize the capacity of bolt load transfer through bearing stress
$FR_{1.2}$ = Minimize the delay in bolt load transfer

For these functional requirements, the following design parameters are defined:

$DP_{1.1}$ = Bolt diameter
$DP_{1.2}$ = Bolt hole clearance

For the second functional requirement (delay adhesive failure), the clamping force needs to be applied on the flat plates and distributed on the largest possible area. The functional requirements for the second level can then be stated as:

$FR_{2.1}$ = Distribute the compressive stress (near the edge of the overlap)
$FR_{2.2}$ = Ensure a compressive stress

The corresponding design parameters are then:

$DP_{2.1}$ = Compression stress distributor (large base of bolt head or washer)
$DP_{2.2}$ = Bolt pretension

To minimize the secondary bending (FR_3), two children are identified. The first one requires increasing the bending stiffness. However, since the secondary bending is the result of an offset between the load paths of both flat plates, it is possible to reduce the secondary bending by reducing the bending moments generated by the external load. The second level of decomposition for FR_3 then becomes:

$FR_{3.1}$ = Increase bending stiffness
$FR_{3.2}$ = Minimise secondary bending moments

The following design parameters are then defined:

$DP_{3.1}$ = Flat plates' thicknesses
$DP_{3.2}$ = Positioning of neutral axis (i.e. composite stacking sequence)

Finally, to improve the load distribution inside the joint (FR_4), a study can be performed following several physical sections. In the case of a joint with multiple bolts, the joint can be split in two general sections; the zones between the bolts and the zones between the bolts and the free edges. In general, shear stress tends to be higher near the free edges [Lees and Makarov, 2004]. To reduce the stress level in these zones, some of the load should be redirected between the bolts. The two following functional requirements are thus derived:

$FR_{4.1}$ = Increase the adhesive load transfer between the bolts
$FR_{4.2}$ = Reduce the load transfer near the free edges

The corresponding design parameters are:

$DP_{4.1}$ = Different adhesive between the bolts
$DP_{4.2}$ = Reduced flat plate rigidity near the free edges.

The final matrix of the hybrid joint is shown in Figure 4. The position of the coupling between the different parameters of the joint results in a coupled matrix. The amount of coupling in this matrix makes it impossible to obtain a decoupled matrix by reorganizing the FR-DP order without redefining the FRs or DPs.

	DP_1	$DP_{1.1}$	$DP_{1.2}$	DP_2	$DP_{2.1}$	$DP_{2.2}$	DP_3	$DP_{3.1}$	$DP_{3.2}$	DP_4	$DP_{4.1}$	$DP_{4.2}$
FR_1	X	0	0	0	0	0	X	0	0	X	0	0
$FR_{1.1}$	0	X	0	0	0	0	0	X	X	0	0	0
$FR_{1.2}$	0	0	X	0	0	0	0	0	0	0	X	X
FR_2	X	0	0	X	0	0	0	0	0	0	0	0
$FR_{2.1}$	0	X	0	0	X	0	0	0	0	0	0	0
$FR_{2.2}$	0	X	0	0	X	X	0	0	0	0	0	0
FR_3	0	0	0	X	0	0	X	0	0	0	0	0
$FR_{3.1}$	0	0	0	0	0	0	0	X	0	0	0	0
$FR_{3.2}$	0	0	0	0	X	0	0	X	X	0	0	0
FR_4	X	0	0	0	0	0	X	0	0	X	0	0
$FR_{4.1}$	0	X	X	0	0	0	0	0	0	0	X	X
$FR_{4.2}$	0	X	X	0	0	0	0	X	X	0	X	X

Figure 4. FR-DP matrix of second level decomposition.

4 REMOVING DESIGN COUPLING

4.1 FIRST LEVEL OF DECOMPOSITION

To reduce the coupling between the children of FR_1 and the other FRs, it is necessary to review some FRs and DPs. The approach we propose is to remove $FR_{1.1}$ (maximize the capacity of bolt load transfer through bearing stress). Following the Hart-Smith [2003] guidelines when addressing bearing stress in bolted composite joints, the diameter of a bolt should be close to the thickness of the laminates for thicknesses below 10mm. Also, since an FR cannot have only one child [Suh, 2001], $FR_{1.2}$ (minimize the delay in bolt load transfer) can be reorganised as a child of FR_4 (in-plane rigidity of the joint). FR_1 is then removed and the first level of decomposition becomes:

FR_1 = Delay adhesive failure (crack initiation and propagation)
FR_2 = Minimize the secondary bending
FR_3 = Uniformly distribute the load inside the joint

Based on the literature review presented in section 2, the corresponding design parameters can be defined as follows:

DP_1 = Clamping force (compression stress)
DP_2 = Bending stiffness of flat plates
DP_3 = In-plane rigidity of flat plates

The design matrix obtained after the first level of decomposition is shown in Figure 5. At this stage in the FR-DP decomposition of this problem, no coupling is apparent.

	DP_1	DP_2	DP_3
FR_1	X	0	0
FR_2	0	X	0
FR_3	0	0	X

Figure 5. FR-DP matrix of first level decomposition (second iteration).

4.2 Second level of decomposition

Because there wasn't any coupling on the top side of the initial design matrix between FR_1 (maximize the bolt load transfer capacity) and FR_2 (delay adhesive failure), no modifications were required to FR_2's children. Therefore, after renumbering to FR_1, the result is:

$FR_{1.1}$ = Distribute the compression stress (near the edge of the overlap)
$FR_{1.2}$ = Ensure a compressive stress

The corresponding design parameters are then:

$DP_{1.1}$ = Compression stress distributor (large bolt head base or washer)
$DP_{1.2}$ = Bolt pretension

The removal of $FR_{1.1}$ (maximize the capacity of bolt load transfer through bearing stress) from the last iteration has also removed the coupling with $DP_{3.1}$ (flat plates thickness) and $DP_{3.2}$ (positioning of neutral axis). Therefore, no modifications are required for FR_3 (minimize the secondary bending) and its children. After renumbering to FR_2, the result is:

$FR_{2.1}$ = Increase bending stiffness
$FR_{2.2}$ = Minimise secondary bending moments
$DP_{2.1}$ = Flat plates thickness
$DP_{2.2}$ = Positioning of neutral axis

The last functional requirement now has a third child, which is $FR_{1.2}$ (minimize the delay in bolt load transfer) from the last iteration. Because of the existing coupling between $DP_{4.1}$ (different adhesive between the bolts) and $DP_{4.2}$ (reduced flat plate rigidity near the free edges) from the last iteration, $DP_{1.2}$ has been renamed to: minimal bolt hole clearance. By doing so, the effect of $DP_{4.1}$ and $DP_{4.2}$ will be very limited and the coupling can be removed. However, this will be achieved only if the corresponding process variable can ensure a tight tolerance during manufacturing and assembling.

Finally, because of the coupling between $FR_{4.1}$ and $FR_{4.2}$, it has been decided to rename $FR_{4.2}$ to specify that the reduction in rigidity near the free edges is required. By renaming $DP_{4.2}$ to a more specific solution (tapered edges), an uncoupled design can be achieved. The final solution is then:

$FR_{3.1}$ = Minimize the delay in bolt load transfer
$FR_{3.2}$ = Increase the adhesive load transfer between the bolts
$FR_{3.3}$ = Reduce flat plate rigidity near the free edges
$DP_{3.1}$ = Minimal bolt hole clearance
$DP_{3.2}$ = Stiffer adhesive between the bolts
$DP_{3.3}$ = Tapered edges

Figure 6 shows the final design matrix obtained after the FR-DP decomposition. The final result is a decoupled matrix. Based on this decomposition, physical integration will be used to propose an optimized joint configuration.

	DP_1	$DP_{1.1}$	$DP_{1.2}$	DP_2	$DP_{2.1}$	$DP_{2.2}$	DP_3	$DP_{3.1}$	$DP_{3.2}$	$DP_{3.3}$
FR_1	X	0	0	0	0	0	0	0	0	0
$FR_{1.1}$	0	X	0	0	0	0	0	0	0	0
$FR_{1.2}$	0	X	X	0	0	0	0	0	0	0
FR_2	X	0	0	X	0	0	0	0	0	0
$FR_{2.1}$	0	0	0	0	X	0	0	0	0	0
$FR_{2.2}$	0	X	0	0	X	X	0	0	0	0
FR_3	0	0	0	X	0	0	X	0	0	0
$FR_{3.1}$	0	0	0	0	0	0	0	X	0	0
$FR_{3.2}$	0	0	0	0	0	0	0	X	X	0
$FR_{3.3}$	0	0	0	0	X	X	0	X	0	X

Figure 6. FR-DP matrix of second level decomposition (second iteration).

5 PHYSICAL INTEGRATION

One of the major design components defined in section 4 is the application of a clamping force on the joint. Fu and Mallick [2001] showed that the addition of a clamping force can effectively reduce the maximal peel stress in the adhesive layer near the edge of the overlap if the clamping force is distributed onto this area. For their analysis, the authors used thick flat washers. However, unless the washers have very high rigidity, their deformation under bolt pretention can prevent an even distribution of this pretention under the entire washer surface. The actual result might be similar to what is shown in Figure 7. If such is the case, then the addition of washers might have a very limited result on performance while having a significant result on the overall mass of the joint.

Therefore, a new type of washers based on Belleville springs is proposed. The idea is to impose the washers to come into contact with the flat plates as far as possible from the bolt shank and as close as possible to the overlap edge. By doing so, the zone under compression can be much closer to the edge of the overlap without increasing the washers thickness and weight. A proposed design is provided in Figure 8.

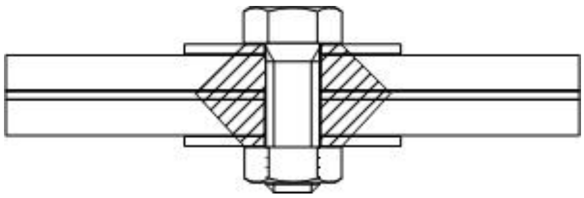

Figure 7. Zone in compression under bolt pretension using a flat washer.

The other modification to the initial geometry introduced during physical integration is adding tapered edges to the flat plates as shown in Figure 8. This reduction in thickness near the edges has two effects. First, as required by DP3.3, the local in-plane rigidity of the plates is lowered by reducing the thickness of the flat plates. This should diminish the load transferred locally. The second effect is to bring the neutral axis closer to the joint central plane, thus reducing local secondary bending moments as required by $DP_{2.2}$.

Finally, as stated in $DP_{3.2}$, a second adhesive has been introduced between the two bolts. The objective of this change is to reduce the load transferred near the free edges of the joint by increasing the rigidity between the bolts. More loads should then be transferred in the stiffer load path created by the stiffer adhesive. This approach showed promising results in the work done by Fitton and Broughton [2005].

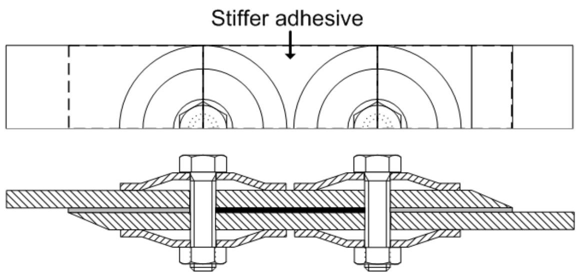

Figure 8. Joint Geometry after physical integration.

6 EVALUATION OF THE SOLUTION

The evaluation of the solution is done through the use of finite element analysis. Two different analyses were performed and compared to show the improvement obtained with the proposed solution. Both analyses were performed using 3D parametric finite element modelling in ANSYS APDL V13.0.

6.1 GEOMETRY

The initial geometry analysed is shown in Figure 9. For both analyses, the geometry uses two bolts with a pretension of 1500N per bolt. Figure 10 shows the dimensions of the proposed solution obtained through physical integration.

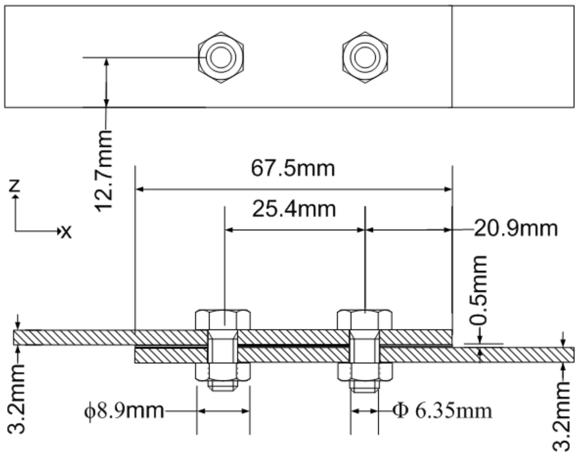

Figure 9. Dimensions of the baseline geometry analysed.

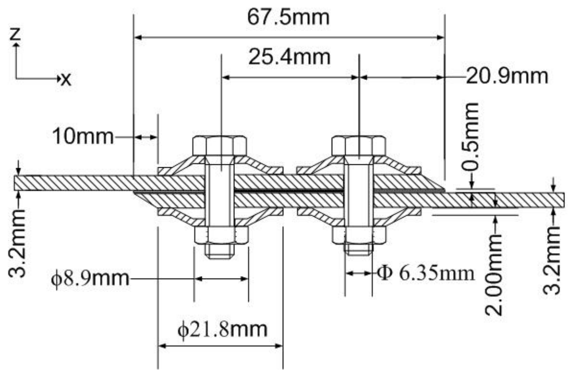

Figure 10. Dimensions of the new joint geometry analysed.

6.2 MATERIALS

For this analysis, the materials were chosen based on the work done by Kelly [2005; 2006]. The results published by the author were used to compare the quality of the initial finite element model. The laminates are made of carbon fiber/epoxy unidirectional prepreg (T700/Epicote 828LV) with the properties shown in Table 1.

For the baseline analysis, the chosen adhesive is a polyurethane adhesive (Pilogrip 7400/7410). For the new joint geometry, the polyurethane adhesive was used between the bolts and the free edges. A stiffer epoxy adhesive (Epibond 1590 A/B) was used between the two bolts. Both adhesives were modeled using non-linear stress-strain curves as presented by Kelly [2005; 2006].

Table 1. Composite material properties [Sjögren *et al.* 2001].

Parameter	Value
E_{11}	140 GPa
E_{22}	10 GPa
E_{33}	5.2 GPa
ν_{12}	0.3
ν_{13}	0.3
ν_{23}	0.5
G_{12}	5.2 GPa
G_{13}	5.2 GPa
G_{23}	3.9 GPa

Both geometries were modelled using the same quasi-isotropic stacking sequence $[0,+45,-45,90]_{S2}$, resulting in a total laminate thickness of 3.2mm (0.2mm per layer). For this analysis, it has been decided not to evaluate the effect of $DP_{2.2}$ (positioning of neutral axis) through the use of the stacking sequence. The decision to remove this parameter from the final analysis was made because this change can have major impact on the overall behaviour of the plates outside the overlap combined with the fact that Stewart [1997] showed the impact of such a change on a hybrid joint.

6.3 RESULTS

Figure 11 shows the difference in rigidity (joint displacement resulting from the external force) between both geometries. As expected, the addition of a stiffer adhesive between the two bolts greatly increased the rigidity of the joint.

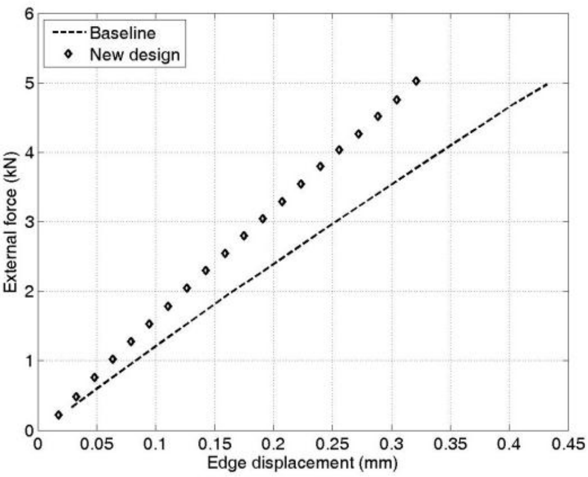

Figure 11. Comparison of the joints rigidity.

The load transfer ratio between the bolts and the adhesive joint is presented on Figure 12. This measure is the result of a summation of the reaction forces on the contact interface between the bolt shank and the flat plate holes. We may expect that a certain amount of the load also transits through friction between the washers and the flat plates but this load transfer should not be as important as in a high preloaded metallic joint.

As it can be seen, the load transferred by the bolt greatly decreases with the new geometry. This change can be attributed to the stiffer adhesive between the two bolts, thus transferring more load. With such a low level of load transferred by the bolt, adhesive or adherent failure should occur before bearing failure. As one objective of this project is to improve the effectiveness of load transfer inside the joint, additional solutions should be evaluated to increase the bolt load transfer ratio.

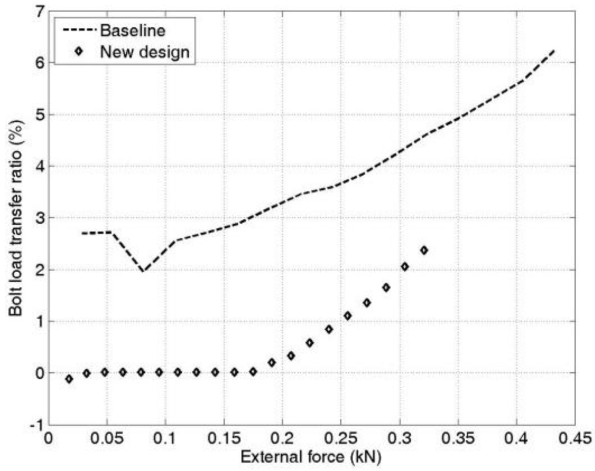

Figure 12. Comparison of the bolt load transfer ratio.

Figure 13 shows the comparison of the maximal peel stress in the joint. The results show a clear reduction of the minimal peel stress in the compression zone near the bolts. This change can be attributed to the increased contact surface provided by the washers. It also has the advantage of providing the capability for higher bolt pretention forces before damaging the flat plates or inducing plastic deformation. The maximal peel stress is also greatly reduced, which was one of the main goals of the new geometry. By reducing the maximal peel stress in the adhesive by almost a factor of 2, the joint should withstand higher static and fatigue loads before failure.

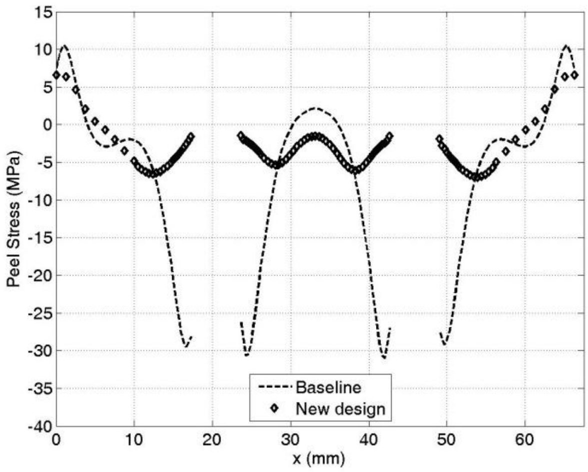

Figure 13. Comparison of the adhesive peel stress (measured in the middle plan of the joint).

Finally, Figure 14 shows the comparison of the shear stress in the adhesive layer. As it can be seen, the maximal shear stress is slightly higher within the new design. The deformation of the flat plates increased near the edges, which resulted in a higher shear stress level in these areas. However, before rejecting this solution, additional analysis should be performed with different parameter values. The length of the chamfer or the area ratio of each adhesive should be further analysed as well as providing bonding line spew on the edge that demonstrated improved behaviour in bonded joints [Taib, 2006].

It is also possible that other parameters that were not considered in this analysis might have an influence on load transfer and shear stress. The effect of friction between the washers and the flat plates may be further investigated as a result of the bolt preload, but restrained by the compression limits of the composites as well as by the creep effects.

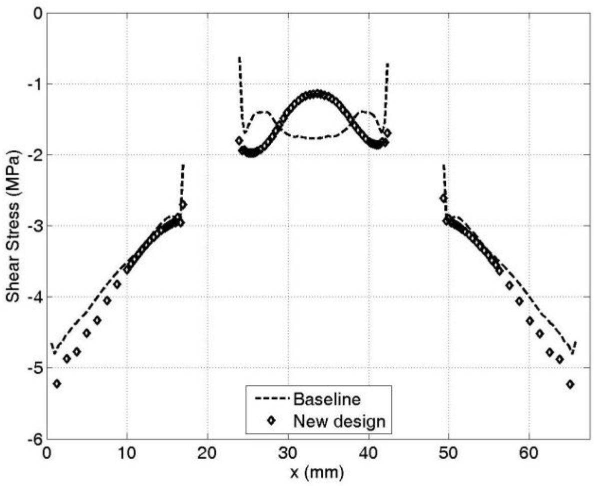

Figure 14. Comparison of the adhesive shear stress (measured in the middle plan of the joint).

7 CONCLUSION

This work proposed a new geometry for single lap hybrid joints. This geometry is issued from an Axiomatic Design decomposition. With the functional requirements and design parameters defined, physical integration was used to propose a new joint geometry that successfully reduces the maximum peel stress inside of the adhesive layer. Because single lap joints tend to fail due to crack propagation initiated by high peel stress in the adhesive, this new geometry shows promising applications where high static strength and fatigue life are required.

However, the objective of reducing the maximum shear stress in the adhesive was not achieved with the selected values of each design parameters. Future work should be conducted to analyse the effect of the stiffness ratio between bonded areas. Also, additional knowledge should be gathered concerning the amount of external load transferred by friction under the washers and generally by the bolts as their contribution to the general performance of the joint should be optimized. Increasing the amount of load transferred by the bolts may help to reduce shear stress in the adhesive layer.

8 REFERENCES

[1] Bois C., Colt M., Wargnier H., Wahl J.-C., "Étude du tranfert de charge dans les assemblages composites hybrides boulonnés et collés", *JNC 17 - 17èmes Journées Nationales sur les Composites*, 2011.

[2] Chan W.S., "Analysis of composite bonded/bolted joints used in repairing", *Journal of Composite Materials*, Vol. 32, No. 12, pp. 1045-1061, 2001.

[3] Fu M., & Mallick P. K., "Fatigue of hybrid (adhesive/bolted) joints in SRIM", *International Journal of Adhesion and Adhesives*, Vol. 21, pp. 145-159, 2001.

[4] Hart-Smith L.J., "Bonded-Bolted Composite Joints", *Journal of Aircraft*, Vol. 22, No. 11, pp. 993-1000, 1985.

[5] Hart-Smith L.J., "Design and Analysis of Bolted and Riveted Joints in Fibrous Composite Structure", in Recent advances in Structural Joints and Repairs for Composite, Tong L. & Soutis C. (ed.), Springer, pp. 211-257, 2003.

[6] Kelly G., "Load transfer in hybrid (bonded/bolted) composite single-lap joints", *Composite structures*, Vol. 69, No. 1, pp. 35-43, 2005.

[7] Kelly G., "Quasi-static strength and fatigue life of hybrid (bonded/bolted) composite single-lap joints", *Composite structures*, Vol. 72, No. 1, pp. 119-129, 2006.

[8] Kumar B., Sun C. T., Wang P. H., "Adding Additional Load Paths in a Bonded/Bolted Hybrid Joint", *Journal of Aircraft*, Vol. 47, No. 5, pp. 1593-1598, 2010.

[9] Kweon J.H., Jung J.-W., Kim T.-H., Choi J.-H., Kim D.-H., "Failure of carbon composite-to-aluminum joints with combined mechanical fastening and adhesive bonding", *Composite structures*, Vol. 75, No. 1-4, pp. 192-198, 2006.

[10] Lees J. M., & Makarov G., "Mechanical/bonded joints for advanced composite structures", *Proceedings of the Institution of Civil Engineers: Structures and Buildings* Vol. 157, No. 1, pp. 91-97, 2004.

[11] Lin W.-H., & Jen M.-H. R., "The Strength of Bolted and Bonded Single-Lapped Composite Joints in Tension", *Journal of Composite Materials*, Vol. 33, No. 8, pp. 640-666, 1999.

[12] McCarthy C.T., McCarthy M.A., "Three-dimensional finite element analysis of single-bolt, single-lap composite bolted joints: Part II—effects of bolt-hole clearance", *Composite Structures*, Vol. 71, No. 2, pp. 159-175, 2005.

[13] Oterkus E., Barut A., Madenci E., Ambur D., "Analysis of bolted-bonded composite lap joints", *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, April 2007.

[14] Paroissien E., Sartor M., Huet J., "Hybrid (Bolted/Bonded) Joints Applied to Aeronautic Parts: Analytical One-Dimensional Models of a Singlelap Joint", *6th International Conference on Integrated Design and Manufacturing in Mechanical Engineering*, Grenoble, 2006.

[15] Paroissien E., Sartor M., Huet J., Lachaud F., "Analytical Two-Dimensional Model of a Hybrid (Bolted/Bonded) Single-Lap Joint", *Journal of Aircraft*, Vol. 44, No. 2, pp. 573-582, 2007.

[16] Sawa T., Kobayashi T., Fujii T., "Strength of combination joints of an adhesive with bolts (T-flange adherends subjected to an external bending moment)". *JSME International Journal, Series 1: Solid Mechanics, Strength of Materials* Vol.32, No. 3, pp. 411-419, 1989.

[17] Sjögren A., Krasnikovs A.,Varna J., "Experimental determination of elastic properties of impact damage in carbon fiber/epoxy laminates". *Composite Part A: applied science and manufacturing,* Vol.32, pp. 1237-1242, 2001.

[18] Stewart, M. L., "Experimental investigation of composite bonded and/or bolted repairs using single lap joint designs". *38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference,* pp. 2752-2760, Kissimmee, FL, 1997.

[19] Suh, N.P., *The principles of design*. New York: Oxford University Press, 1990. ISBN 978-0-19-504345-7.

[20] Suh, N.P., *Axiomatic design : Advances and applications*, New York: Oxford University Press, 2001. ISBN 978-0-19-513466-7.

[21] Taib, A, Boukhili, R., Achiou, S., Gordon, S., Boukehili, H., Bonded joints with composite adherends. Part I. Effect of specimen configuration, adhesive thickness, spew fillet and adherend stiffness on fracture, *International Journal of Adhesion&Adhesives 26*, pp. 226-236, 2006.

