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PRAGMATIC DESIGN RULES FOR SELECTIVE LOAD INTRODUCTION IN STRUCTURAL SHEETS

Michael Niedermeier[1], Markus Henne[2], David Keller[3], Gerald Kress[3], Ralf Stetter[1]
(1) UAS Ravensburg-Weingarten, Germany, (2) IWK of UAS Rapperswil, Switzerland, (3) Center of Structure Technologies ETH Zurich, Switzerland

ABSTRACT

Good joint design is vital to the success of the product. Spot joining methods in particular cause critical stress concentrations in structures using composite materials. One way of avoiding these is to use the “onsert”, which is a joining element for transmitting loads into structural sheets or sandwich materials such as are typical in transportation applications. The onsert is simply bonded to the surface of the otherwise unharmed substrate. Thus, in contrast to other joining methods such as inserting, riveting or bolting, onserts avoid weakening the substrate.

This paper describes a pragmatic way to design onserts, embodying notions of a synectic process and biomimetic techniques. The methods are illustrated by the design of an onsert for FRP panels, which was simulated numerically and tested in practice. Design rules are proposed.

Keywords: composite material, joint design, onsert, anisotropy, synectic, biomimetic, design rules

1 INTRODUCTION

A successful product requires a holistic design process covering the choice of materials and the production process as well as the disassembly of the product at the end of its lifetime. The past two or three decades have seen rapid development of new materials such as fiber reinforced materials as well as new metal alloys. In parallel with the quest for ever-improved performance, the increasing variety of available structural materials has promoted advances in multi-material technologies. In turn, this has lead to an increasing demand for bonding systems that can join two different materials. Table 1 lists some existing joining methods for various pairs of material combinations and for three geometrical characteristics of the joint. It shows that the choice of joining methods is more limited for multi- than for mono-material applications. The geometrical characteristics must be considered in selecting the right method. As in Table 1, the joint types can be classified as 0-dimensional: spot joints, 1-dimensional: linear joints, and 2-dimensional: joints over areas.

Two-dimensional joints are typically made by brazing for metal-to-metal combinations, and by adhesive bonding for multi-material combinations. In contrast, metal-to-metal line joints are usually welded, while hemming is mostly used for such joints between metal sheets and plastic composites. The most severe stress distributions occur in spot joints. Spot joining of multi-material combinations such as continuous fiber reinforced plastics with a metallic structure is mostly carried out by riveting. Two examples of this are blind riveting and self-piercing riveting. In blind riveting a clearance hole is drilled through both parts and the blind rivet, plugging the hole and deforming plastically, joins the parts by clamping. Self piercing riveting requires no drilling, the upper sheet being cut by the edges of the rivet while the lower one is deformed by a female die, so forming an interlocking joint. In both cases the structure is locally destroyed, and very high peak stresses are induced which are difficult to calculate. The most difficult situation is the riveting of a composite, e.g. a continuous fiber reinforced plastic product. In the riveting process the reinforcing fibers are cut through with the result that the force flow must be deflected around the rivet.

One way of minimizing the stress inhomogeneities in a spot joint is by an optimally designed “onsert”, as shown in Figures 1 and 2. The optimal shape of the onsert – i.e., that which results in maximum strength - depends on many parameters such as the material properties and geometry of the parts to be joined. Specifically, it will depend very much on the structural properties of the substrate. Optimizing onsert shapes is thus a very complex task.

Table 1. Geometrical aspects of selected joining technologies [2]

	Materials to be joined		
Geometry	Mono-material e.g. aluminum / aluminum	Multi-metal e.g. aluminum / steel	Multi-material e.g. aluminum / plastic composite
Spot (0-dimensional)	self-piercing riveting blind riveting clinching spot welding stud welding threaded fastening bolting onsert	self-piercing riveting blind riveting clinching threaded fastening bolting onsert	self-piercing riveting blind riveting insert (threaded fastening) bolting onsert
Line (1-dimensional)	welding (e.g. fusion, laser, friction stir, …) hemming onsert / outsert	brazing hemming onsert / outsert	hemming onsert / outsert
Area (2-dimensional)	bonding brazing	bonding brazing	bonding

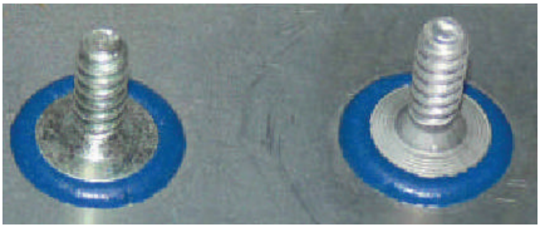


Figure 1: Commercial aluminum onserts (head diameter 12mm, Raybond^{TM}) bonded to aluminum car body sheet with epoxy adhesive

2 SYSTEMATIC APPROACH

This section describes the systematic approach that was chosen for designing onserts, together with the rationale for the choice and begins with a review of the most prominent existing approaches to design.

2.1 State of the art

For systems whose main purpose is to transmit forces or moments from one part to another, a number of design researchers [3, 4, 5, 6, 7] recommend for mechanical products an approach based on the flow of forces.

This approach is mainly helpful if the core ideas for a new product or system already exist. In the literature little support is given for the creative process of generating new ideas for systems that serve to transmit forces and moments. In lightweight engineering it has been proven that designs based on biomimetic principles always require the least energy to produce, are the lightest and last longest [8].

Therefore biomimetic approaches can generally be taken as appropriate for supporting the generation of new ideas for systems that transmit forces and moments. Ways of integrating biological design principles into industrial products are referred to using the terms “bionics” [9, 10, 11] and “synectics” [12].

Ehrlenspiel [13] defines synectics as a method for solving problems and generating ideas that is characterized by the use of analogies from non-technical areas such as biology. This approach was chosen for the development of the onserts, but nonetheless the principles of biomimetics and mathematical optimization were applied as well.

The starting-point of the design is a conical aluminum onsert with a disc diameter of 60mm (Figure 2). The load is introduced by an M8 threaded fastener. To begin with only tensile loads are assumed. The substrates vary from isotropic metals to anisotropic composite like continuous fiber reinforced laminates. The onsert is secured to the substrate with a two-component epoxy adhesive.

Figure 2:Conical aluminum onsert, disc diameter 60mm, M8 threaded fastener

2.2 Function

The main function of a joint is to transmit forces or moments, that is to carry the force flow through the product, and it always introduces a discontinuity into the structure. The geometry of the joint affects its stiffness for a given loading, and this stiffness in turn determines the characteristic stress distribution and the peak stresses.

Stiffness is in general a function of geometry and the Young´s modulus of the material. The material moduli for an anisotropic material like a continuous fiber reinforced plastic can be decided within certain limits by the choice of fiber orientation.

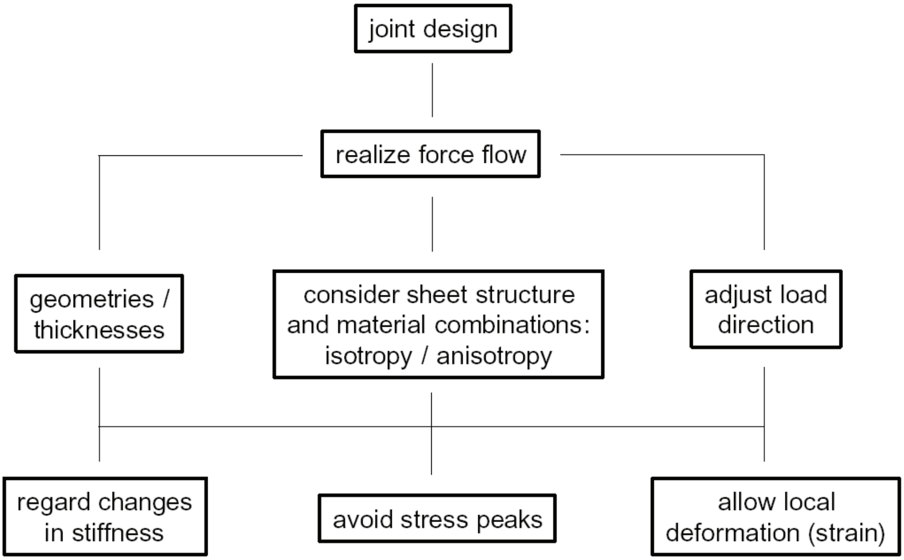


Figure 3: Functions, demands and constraints

2.3 Synectics

Synectics is a problem-solving methodology developed by Gordon in 1961 [12]. In particular it uses non-technical analogies to create ideas for technical solutions.

According to reference [13] the sequence of steps in synectics is:

1. Define the problem.
2. Analyze and understand the problem.
3. Search for analogies in other areas of life, i.e. non-technical analogies.
4. Analyze the collected analogies.
5. Compare them to the technical problem.
6. Develop ideas based on the analogies.
7. Develop a solution.

In the present case this means:

1. Problem: *realize force flow* through a spot by an optimized design.
2. Analyze the problem:
   Understand the problem: *avoid stress peaks*, e.g. those caused by drillings. Consider anisotropy and *changes in stiffness*.
3. Search for non-technical analogies (Table 2): examples are the gecko's toes, cuttlefish tentacles with acetabula, spiders' feet, climbing plants, the shape of a drop falling into water.
4. Analysis of the analogies:

   The gecko's toe is divided into adhesive disks. These take the form of transverse lamellae. A lamella on the other hand consists of millions of hook-shaped hairs. Adhesion is due to van der Waals forces [14].

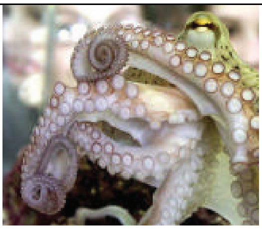
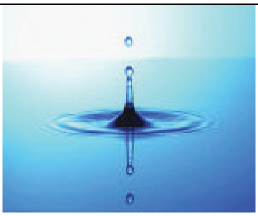
   Most arthropods produce a glue-like liquid that permits them to stick to a wall. The spider however uses the same strategy as the gecko - van der Waals forces [15].

   The cuttlefish's tentacles hold on thanks to the vacuum in the flexible acetabula (suckers).

   A climbing plant needs a certain surface roughness. Different plants use different mechanisms, varying from interlocking to adhesive bonding.

   The shape of a water drop falling into water minimizes the surface energy based on the surface tension of the water. The shape boundary is of paraboloidal sections [16].

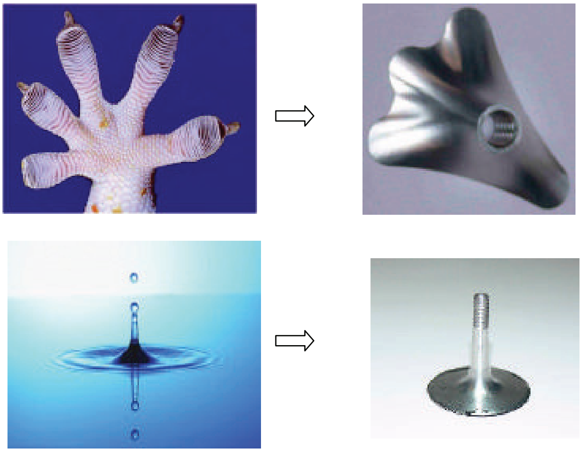
Table 2. Synectics: selected analogies

Analogy		Principle
Gecko foot	 [picture I. Rechenberg, TU Berlin]	Toes with micro-hairs ⇨ van der Waals forces ⇨ adhesion
Spider feet	 [picture www.spinnenfreund.de]	Toes with micro-hairs ⇨ van der Waals forces ⇨ adhesion
Cuttlefish tentacles	 [picture www.schulmodell.de]	Tentacles with acetabula (suckers) ⇨ flexible skin ⇨ vacuum
Climbing plant	 [picture www.gartenpflege-service.de]	Arms with increased contact surface ⇨ adhesion
Drop of water falling in water	 [picture IHK Reutlingen]	Shape minimizes surface energy

5. Comparison to the technical problem and development of ideas based on analogies:

Figure 4 shows two possible solutions for the problem of transmitting a single-point load to a structural sheet, the first based on the gecko's toe and the second on the water drop.

1. The gecko onsert has toe-shaped swellings, whose directions match the anisotropy of the substrate. The contact area between onsert and substrate has a defined roughness analogous to the micro-hairs of the gecko's toes. The bonding is adhesive, e.g. a two component epoxy adhesive.
2. The water drop design can be described as a multipurpose solution. The anisotropy of the substrate is not considered. The main idea is to transfer the energy-minimized shape of the fallen liquid drop to a rigid onsert. The aim is to get a homogeneous stress distribution in the complete set-up. Nevertheless this idea needs to be verified and it cannot be used directly for optimizing the onsert design.



1.

Gecko design:
- ⇨ toes in directions of substrate anisotropy
- ⇨ rough surface analogous to hair
- ⇨ bonding by adhesive

2.

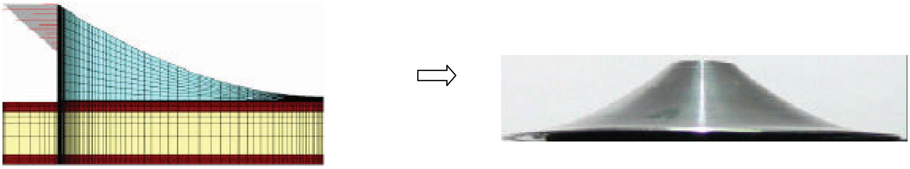
Water drop design:
- ⇨ shape as a copy of the boundary of a dipping drop
- ⇨ wave propagation represented in the plate
- ⇨ bonding by adhesive

Figure 4: Two possible ideas based on analogies

3 SOLUTION

3.1 Numerical aspect

Prior investigations by Kress et al. [1, 17] on a rotationally symmetric onsert problem identified the stress distribution in the bonding layer as a suitable criterion for classifying the strength of onsert systems. Maximum bonding strength in an onsert design with a given bonding surface area can be achieved by eliminating stress concentrations which would lead to local failure at low loads. Thus, a homogeneous distribution of some appropriate measure of the stress in the bonding layer (e.g. the von Mises equivalent stress) maximizes the load-bearing capacity of the bond. Following this approach the thickness distribution of an onsert was successfully optimized for maximum strength, using non-linear methods. The resulting shape (Figure 5) showed good results in numerical simulations as well as in mechanical tests.

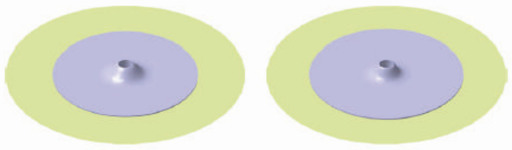


FEM mesh layout
for onsert model with substrate

Turned aluminum onsert,
diameter 60mm

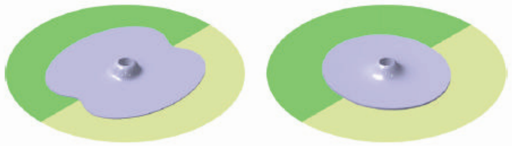
Figure 5: Optimised onsert shape [1,17]

The investigations by Keller [18] describe how the properties of the substrate affect the shape of onsert systems designed for maximum strength. Fiber reinforced panels typically show an anisotropic material behavior. Figure 6 illustrates the effect of this anisotropy on optimal onsert shape for the case of an axial tensile load.



(a) Rotationally symmetric onsert on isotropic substrate

(b) Rotationally symmetric onsert on orthotropic substrate



(c) Quarter-symmetric onsert on orthotropic substrate

(d) Quarter-symmetric onsert on orthotropic sandwich substrate

Figure 6: Optimal onsert shapes for different substrates [8]
In (c) and (d) the colours indicate the reference direction of the laminate

3.2 Heuristic process

The heuristic process to find a solution is not at all systematic. A very important aspect is the inspiration obtained by the way of thinking and abstraction [13, 19]. Figure 7 is a diagram relating the complexity of the design to the anisotropy of the substrate.

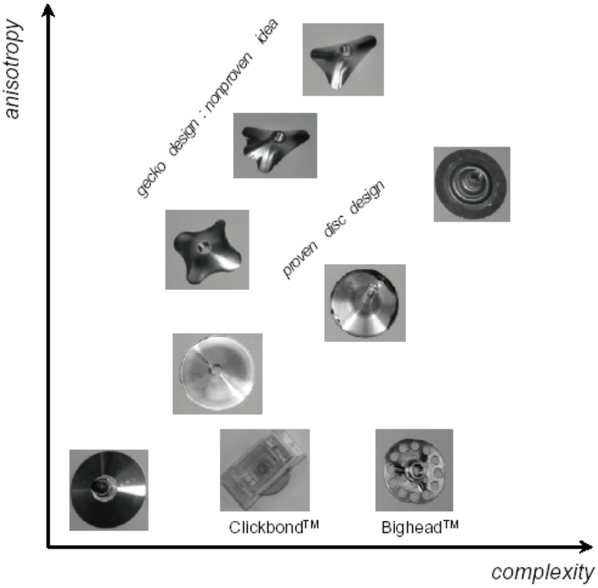


Figure 7: Diagram of possible designs

One aspect which has not been discussed in detail is the type of load and the direction of its application. The onsert designs presented above have to carry dynamic tensile, shear and compressive loads. Adjusting the direction of load application is a very important way of reducing stress concentrations resulting from small manufacturing tolerances (Figure 3).

4 RESULT AND DESIGN RULES

The proposed onsert design is a compromise between manufacturability and adaptability to a variety of substrates – isotropic and anisotropic (Figure 8). The onsert is made of deep drawable aluminum sheet, e.g. EN AW 6016 T4. The Young´s modulus of aluminum, at around 72 GPa, suits nearly every substrate. The adaption of stiffness occurs mainly by virtue of the shape and the sheet thickness. The corrugation of the sheet allows the onsert to adjust itself by plastic deformation, while dynamic loading results in slight elastic deformation, both forms of strain serving to reduce stress concentrations (see the requirement in Figure 3 to “allow local deformation”).

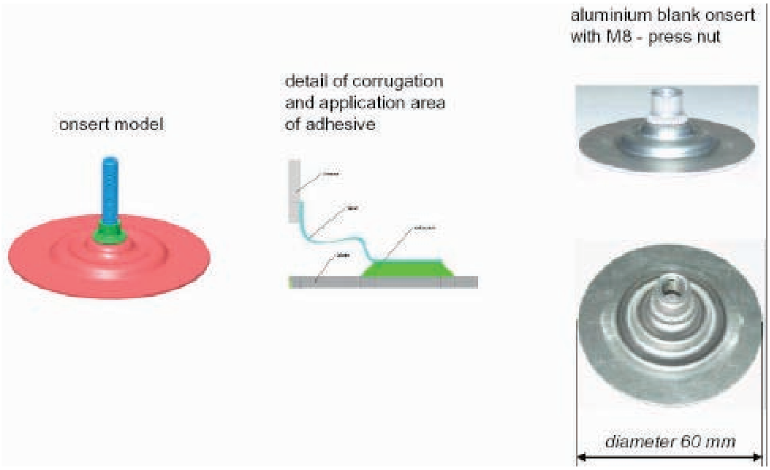


Figure 8: Proposed onsert design, according to reference [20]

The design rules indicated in Figure 3 have thus been observed and confirmed, and may be supplemented by the following as a result of this work:

- Implement smooth stiffness changes by
  - a correct material selection,
  - considering the anisotropy of the substrate,
  - a homogeneous change of onsert thickness depending on the substrate.
- Prefer a symmetric design.
- Open the joining gap slightly or taper the onsert edges where adhesive bonding is used.

5 CONCLUSION

An optimized onsert design has been developed to achieve various levels of structural bonding.
The onsert can be used as multipurpose fastener in transportation applications. Typical products are the fixation of interior sandwich panels and roof systems based on continuous fiber reinforced plastics used in train, bus and aerospace components.

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