DOI: 10.5075/epfl-ICSS12-2018-168-170

IMPROVED FAILURE DESCRIPTION FOR AN ANALYTICAL DIMENSIONING APPROACH FOR INSERTS IN HONEYCOMB SANDWICH ELEMENTS

Johannes Wolff[1], Marco Brysch[2] and Prof. Dr. Ing. Christian Hühne[1]
[1]Institute of Composite Structures and Adaptive Systems, DLR, Braunschweig, Germany. Johannes.wolff@dlr.de
[2] Institute of Adaptronics and Function Integration, Technische Universität Braunschweig. Marco.Brysch@TU-Braunschweig.de

The major requirement for structures of aerospace and ground vehicles is a highly efficient lightweight design i. e. a high stiffness- and strength-to-mass ratio. Due to their outstanding specific bending and shear stiffness, sandwich elements composed of CFRP facings and aluminium honeycomb cores are frequently used as elements of e. g. satellite structures, race car monocoques or lightweight car bodies of passenger train concepts, Fig. 1. To fulfil assembly, maintenance, repair and recycling requirements, connections are often designed as removable, bolted connections. Sandwich core materials typically provide a low local compression resistance. Therefore, cylindrical supporting elements, so called “inserts”, are commonly used to stabilize the core against the clamping force of the screw and to transfer loads into the structure, Fig. 2.

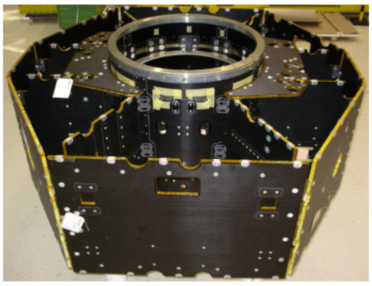

Fig 1: Sandwich structure of the Lisa Pathfinder satellite science module [1].

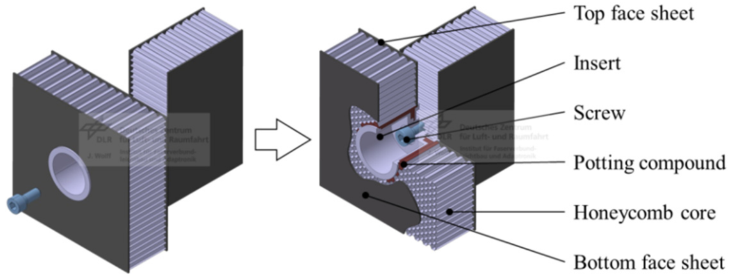

Fig. 2: Bolted t-connection between sandwich panels with a through-the-thickness insert element.

If huge numbers of such inserts are demanded (as e. g. communication satellites can contain insert with numbers up to 25.000, [2]) they can add a remarkable mass proportion to the overall weight of the structure. Since e. g. launching costs of space vehicles reach 10 - 50K$/kg [3–5], a mass minimization of the insert load introductions is worthwhile. In this regard, the objective of this work is to develop an analytical dimensioning method to minimize the diameter $d_i \rightarrow d_{i,min}$ of insert elements loaded with a force $F_{i,n}$, acting normal to the surface of the sandwich. Since through-the-thickness, core connected (resp. potted) inserts are recommended for structural applications, this type of insert is regarded exclusively herein by [6–8], Fig. 3.

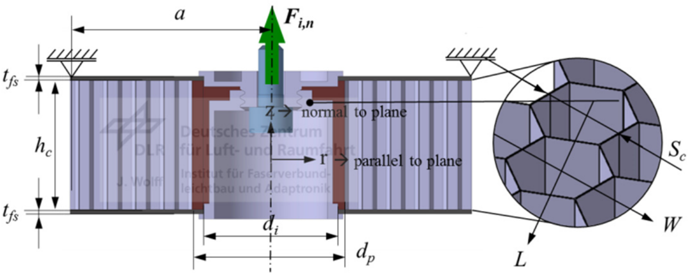

Fig. 3: Schematic insert load introduction with a core connected, two-piece, through-the-thickness insert element.

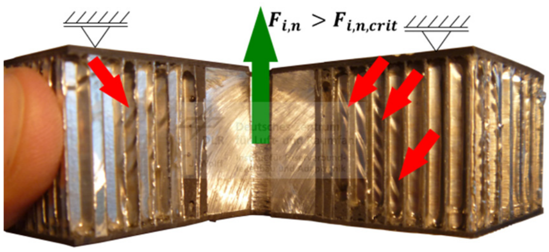

Fig. 4: Plastification of shear deformed cell walls adjacent to the insert (red arrows).

Primary structures of aerospace vehicles must stay undamaged (i. e. without permanent deformations causing a decrease in stability) after they have been exposed to their limit load, according e. g. to specification CS-25, [9]. Therefore, the failure strength ($F_{i,n,crit}$) of any insert load introduction must be superior to the acting force on the insert ($F_{i,ll}$) when the aerospace structure is exposed to its limit load. Therefore, the inserts failure strength, including a safety factor S_1 becomes $F_{i,n,crit} \geq F_{i,ll} \cdot S_1$. Summarizing recent literature, the preliminary damage of an insert load introduction exposed to $F_{i,n} > F_{i,n,crit}$ is a plastification of shear buckled honeycomb core cell walls around the insert, Fig. 4. Regarding ECSS [6] and Hertel [10], this plastification starts when the elastic shear strength of the core material ($\tau_{hc,crit}$), is reached. To avoid this irreversible decrease in stiffness of the insert load introduction, the highest shear stress in the core ($\tau_{c,max}$) may not exceed $\tau_{hc,crit}$. According to ECSS [6], the core shear stress ($\tau_c(r,z)$) increases with $1/r$ near to the insert, Fig. 5. Therefore, $\tau_{c,max}$ is located adjacent to the potting of the insert element, $\tau_{c,max} = \tau_c(r = d_p/2)$, Fig. 6. The minimal insert diameter is found when $\tau_{c,max}$ equals the shear strength of the core, $\tau_{c,max} = \tau_{hc,crit}$. The core shear stress $\tau_c(r,z)$ can also be described as the quotient of core shear force $Q_c(r)$ and related core shear area,

$\tau_c(r) = Q_c(r)/A_{c,\tau}(r)$, [6], Fig. 5. Under condition of $\tau_{c,max} = \tau_{hc,crit}$, the maximal core shear force becomes $Q_{c,max}(r = d_p/2) = Q_{c,ll}$. With $A_{c,\tau}(r) = \pi \cdot h_c \cdot d_p$, $\tau_{hc,crit}$ can be expressed as $\tau_{hc,crit} = Q_{c,ll}/\pi \cdot h_c \cdot d_p$.

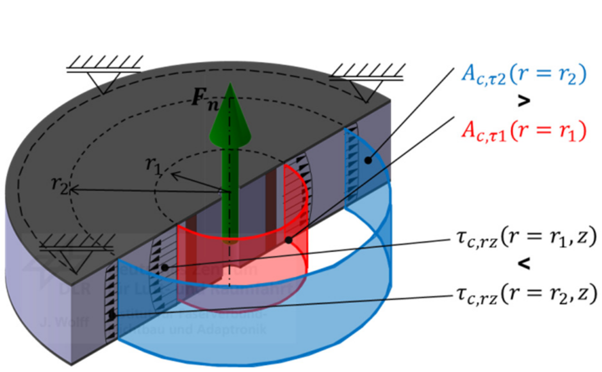

Fig. 5: Decreasing core shear area $A_{c,\tau}$ and increasing core shear stress towards the insert load introduction.

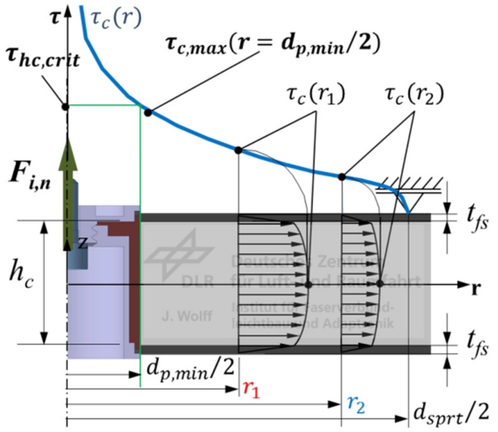

Fig. 6: Course of core shear stress around an insert load introduction.

For a preliminary, rough estimation, the maximal core shear force can be equated with the assumption of $Q_{c,ll} \approx F_{i,o,crit}$, under condition that the sandwich element exhibits thin face sheets and/or a high core height, [6]. With this, an analytical relation between external normal force and insert diameter is found which can be used for a preliminary dimensioning of the insert diameter, Eq. 1.

$$d_{i,min} \approx d_{p,min} \approx \frac{F_{i,n,crit}}{\tau_{hc,crit} \cdot \pi \cdot h_c} \tag{1}$$

Hence, to gain more precise results, three additional factors have to be taken into consideration due to their influence on the minimal insert diameter, [10]. Firstly, there is the relation between the external force $F_{i,n}$ and the internal shear load $Q_c(r)$, secondly the relation of potting-to-insert diameter, $d_i = f(d_p)$ and thirdly the direction depending shear strength of common honeycomb materials, $\tau_{hc,crit,L} \neq \tau_{hc,crit,W}$, Fig. 3.

Regarding the relation of $F_{i,n}$ to $Q_{,c}(r)$, a significant mechanical characteristic of an insert-sandwich system, its statically over determination, has to be considered. It is characteristic for an overdetermined system that the internal loads are distributed to all elements of the system in certain proportions depending on the stiffness ratios between these elements. For this reason, in an insert-sandwich system with flexural rigid face sheets (configuration A, Fig. 7, left), the major proportion of the internal loads is transferred by the face sheets ($Q_{fs,}$ M_{fs} ↑), while the load proportion in the core is significantly reduced (Q_c ↓). Compared to an insert-sandwich system with flexible face sheets (configuration A, Fig. 7, center), the critical shear strength is reached at a considerably smaller distance towards the center of the insert, $d_{p,min,B}/2 < d_{p,min,A}/2$, Fig 7, right.

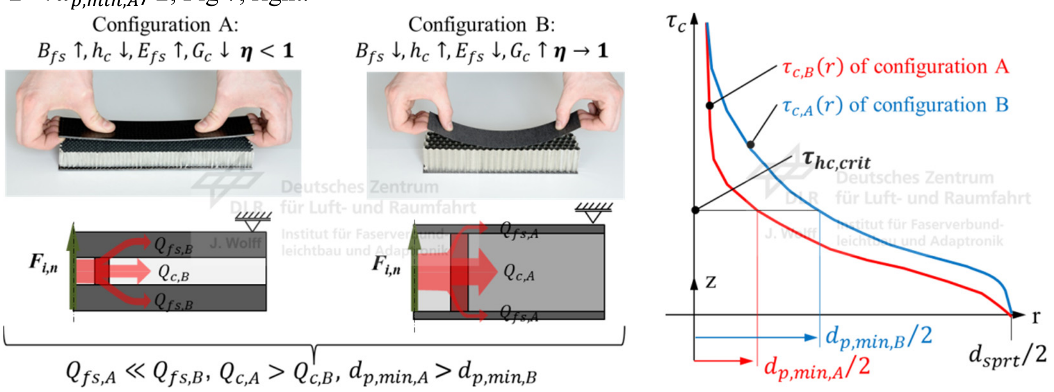

Fig. 7: Sandwich configuration B allows for a smaller insert diameter since the load proportion in the core is reduced.

Youngquist [11] introduced the core shear force reduction factor "k_3" in 1955 to consider the correct relation between $F_{i,n}$ and $Q_c(r = d_p/2)$ depending on the sandwich configuration, $Q_c = F_{i,n} \cdot k_3$ with $0 < k_3 \leq 1$. With k_3 is called η herein, Eq. 1 is extended to Eq. 2.

$$d_{i,min} \approx d_{p,min} = \frac{F_{i,n,crit} \cdot \eta}{\tau_{hc,crit} \cdot \pi \cdot h_c} \tag{2}$$

Due to the static over determination, the reduction factor η can only be determined with the help of either finite element models) or advanced mechanical-analytic models [7, 13, 15-17]. State-of-the-art mechanical-analytic approaches are basing on the higher order sandwich plate theory (HSAPT) due to its ability to solve statically indeterminate problems by integrating additional, independent boundary conditions obtained from e. g. the principle of virtual work. Different HSAPT-models, allowing the calculation of η for different insert types, were provided by Ericksen [15], Thomsen [8] and Bozhevolnaya [18]. Although the Thomsen-model matches best with the specific insert type regarded herein, only the Ericksen- and Bozhevolnaya-models provide usable analytical solution formulations. Unfortunately, both models are only valid for through-the-thickness-inserts without a connection to the core in sandwich elements with only isotropic core materials. Yet Hertel, later cited by ECSS, recommends a modified version of the Ericksen-model usable also for inserts elements with a potted connection to the surrounding core in sandwich elements with honeycomb core material.

Concerning the relation of potting-to-insert diameter in honeycomb cores, it has to be recognized that the potting shape in a honeycomb core is not circular (Fig. 2) like in e. g. sandwich elements with foam core materials. Depending on the borehole center position, different cell numbers where cut and filled with potting afterwards. This results in a spectrum of possible irregular potting forms and quantities.

The irregular potting area can be "smeared" to a theoretically circular, "effective" potting diameter ($d_{p,eff}$), Eq. 3. Hertel [10] provided this analytical formulation, basing on a power function generated from test results. The factors a_1, a_2 and a_3 were derived by different authors independently [6, 10, 19].

$$\mathrm{d}_i = \frac{d_p}{a_1} - \frac{S_c}{a_1} + \frac{a_3}{a_1} \tag{3}$$

The typical manufacturing method of honeycomb materials causes different shear strength levels in the plane parallel directions of the honeycomb grid, $\tau_{hc,crit,L} > \tau_{hc,crit,W}$, Fig. 3. For this, Hertel [10] and Rodriguez [20] provide semi-analytical formulations to smooth the divergent shear strength values to an effective, average shear strength $\tau_{hc,crit,eff}$. Extending Eq. 2 with Eq. 3 and inserting $\tau_{hc,crit,eff}$ now allows the calculation of $d_{i,min}$ of core connected (potted) inserts in sandwich elements with honeycomb cores, Eq. 4.

$$\mathrm{d}_{i,min} = \frac{F_{i,n,crit} \cdot \eta}{a_{1,min} \cdot \tau_{hc,crit,eff3} \cdot \pi \cdot h_c} - \frac{a_{2,min}}{a_{1,min}} \cdot S_c + \frac{a_{3,min}}{a_{1,min}} \tag{4}$$

Yet, Wolff et al. [19] reveal that the results of Eq. 4 show high deviations from experimental results, caused by three reasons. Firstly, the applicability of the Hertel-modified version of the Ericksen-model onto core connected insert types, like it is claimed by Hertel and ECSS, is highly distrusted by the authors, since neither Hertel nor ECSS provide any explanations on their modifications. Secondly, the different approaches to smooth the anisotropic core shear strength of typical honeycomb materials by Hertel and Rodriguez deliver quite deviating results for $\tau_{hc,crit,eff}$. Thirdly, different references claim divergent characteristics of the experimental load-deflection curve to correspond to $F_{i,n,crit,exp}$. Consequently, inacceptable divergences result between the different definitions of $F_{i,n,crit,exp}$. At the ICSS 12, the third issue will be addressed: With the help of a test program, the damage process steps of insert-sandwich systems with core connected, through-the-thickness inserts in honeycomb sandwich elements with different configurations, are analyzed with the help of hysteresis load sequences and cutting samples. This will serve as a basis for a refined, distinct allocation of the critical load $F_{i,n,crit,exp}$ to a characteristic feature of the load-deflection curve. Furthermore, a comparison of experiments to results of an improved version of Eq. 4 will be carried out to show a potential improvement.

The work is financed by the German Aerospace Center within the core funded project Next Generation Train III.

REFERENCES

[1] ESA, „lisa pathfinder," Online, 27.06.2007. http://sci.esa.int/lisa-pathfinder/40832-science-module-structure.

[2] RUAG Schweiz AG, Automating inserts for sandwich panels, *Composites World Vol. 9*, RUAG Space, 2015, p. 12

[3] B. J. Kim et al., Characteristics of joining inserts for composite sandwich panels, *Composite Structures 86*, 2008, p. 55–60.

[4] B. J. Kim und D. G. Lee, Development of a satellite structure with the sandwich T-joint, *Composite Structures 92*, 2009.

[5] D. Brosius, Outer space: The "final frontier" is exciting again! *Composites World Vol. 9*, 2015, p. 6.

[6] ECSS, Space Engineering Insert Design Handbook, ECSS-E-HB-32-22A, *ESA-ESTEC*, 2011.

[7] O. T. Thomsen, Analysis of sandwich panels with through-the-thickness inserts using a HSAPT, *ESA*, 1994.

[8] O. T. Thomsen et al., Analysis and design of sandwich plates with inserts - a HSAPT approach, *Composites B 29B*, 1998.

[9] European Aviation Safety Agency, Certification Specifications for Large Aeroplanes CS-25, Amendment 21, 2007, p. 617.

[10] W. Hertel et al., Standardisation Programme on Design Analysis and Testing of Inserts, Final Report , *ESTEC*, 1981, p. 426.

[11] W. G. Youngquist et al., Stresses induced in a SW- Panel by Load applied at an Insert, *US Department of Agriculture*, 1955.

[12] P. Bunyawanichakul et al., Non-linear FEA of inserts in composite sandwich structures, *Composites B 39*, 2008.

[13] E. Bozhevolnaya et al., Local effects in the vicinity of inserts in sandwich panels, *Composite Structures 35*, 2004, p. 9.

[14] C. Burchardt, Fatigue of sandwich structures with inserts, *Composite Structures 40*, 1998, pp. 201 - 211.

[15] W. S. Ericksen, The bending of circular Sandwich Plate under normal Load, Report, *US Department of Agriculture*, 1953, p. 35.

[16] Y. Frostig et. al, High order theory for sandwich-beam behaviour with transversally flexible core, *J. of Eng. Mech. 118*, 1992.

[17] E. Bozhevolnaya et al., Local effects across core junctions in sandwich panels, *Composite Structures*, 2003, pp. 509-517.

[18] E. Bozhevolnaya et al., Local effects at core junctions of sandwich structures under different types of loads, *CS 73*, 2006.

[19] J. Wolff et al., Pilot study on an analytic sizing tool approach for insert load introductions in sw elements, *ECCM17*, 2016.

[20] J. D. D. Rodriguez Ramirez, Shear testing of honeycomb cores for inserts, *ICCS20*, 2017.