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THE APPLICATION OF 3D PRINTING TECHNOLOGY IN THE DESIGN OF SANDWICH PANELS

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Abstract. Composite materials including sandwich panels can offer a number of advantages such as excellent strength to mass ratio or stiffness to mass ratio. Sandwich panels can find their application in many industrial sectors where the mass and mechanical properties are critical. Despite these and many other advantages, the use of sandwich panels is associated with many problems, which stem from their structural composition (weak core with high shear stiffness connecting two skins with high in plane stiffness). This composition can cause problems in joining the sandwich panels to each other and to other parts by means of mechanical joints. To solve these problems, there exist many accessories such as inserts. The main objective of this paper is to present the development, manufacturing, and testing of plastic inserts for sandwich panels made by Fused Deposition Modelling 3D printing technology.

Keywords: Sandwich panel, 3D printing, fused deposition modelling technology, bonding, pull-out test.

1. Introduction and basic overview

A modern and innovative machine component has to satisfy many aspects. To reach as high strength-to-mass ratio as possible, it is often necessary to use computational optimisation which can ensure an optimal distribution of the material. However, the optimum part shape with optimum material distribution from the point of view of designers and stress engineers is often difficult to produce using conventional technologies. 3D printing technology enables the creative design of machine components. 3D printing makes it possible to produce hollow parts with complex internal structures. Fused Deposition Modelling 3D printing technology (FDM) uses a nozzle to add material layer by layer. This is the main difference from conventional machining, where the material is removed using machining tools. In addition to FDM technology, other 3D printing technologies exist. An overview of these can be found in [1].

Sandwich panels are multi-layer structures consisting of two skins with high in-plane stiffness and strength separated by the core with high shear stiffness and strength. This combination gives very good flexural stiffness in combination with a low specific weight [2]. It is possible to use fibre composites or metal sheets for the skin and, for example, honeycomb or a rigid foam for the core [3]. Sandwich panels can be effectively used in applications where they are subjected to loads distributed to the surface (e.g. pressure field). In the case that point loads (e.g. bolted connections) are required, the use of sandwich panels is possible, but it is necessary to implement inserts for the distribution of the load into the sandwich structure.

Inserts are usually made of metal by machining. In terms of implementation, it is possible to distinguish between two basic categories of inserts – hot bonded inserts and potted inserts. The potted inserts are fitted into holes that are drilled or milled in a finished sandwich panel. The fitting process is, in detail described, in [4]. Hot bonded inserts are fitted during the manufacturing process of the sandwich panel. Therefore, it is necessary to know their position before the manufacturing process [5]. The subject of this paper are potted inserts.

2. Design and load bearing capacity of potted inserts

Commercially available potted inserts usually have the shape of a cylinder with an inner screw thread, see Figure 1 [4]. They are made of metal, by machining, or plastic, by injection. The use of these production technologies is limiting especially for the inner structure of distribution channels. As presented in Figure 1, the shape of distribution channels is usually limited to two holes in the upper headboard of the insert. However, an appropriately designed shape of distribution channels can ensure an optimal distribution of potting compound with a good repeatability, which will improve the scatter in load bearing capacity.

Load bearing capacity of the insert is affected by several aspects. Namely, in addition to the quality of potting, it is the strength and stiffness of the core and skin of the sandwich panel. To obtain the load bearing capacity values, it is necessary to perform experimental pull-out tests. Testing is usually performed based on recommendations given in ESA handbook ECCS-E-HB-32-22A [6]. These tests are not standardised under ASTM International or similar association.

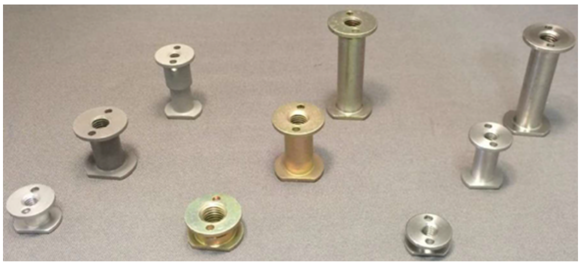


Figure 1. Commercially available potted inserts [4].

The arrangement of the pull-out test is presented in Figure 2.

To obtain a basic estimation of the load bearing capacity, it is possible to use empirical strength equations for the critical load Pcrit, see Equation (1) [6]. It should be noted that other empirical equations for the prediction of the critical load can be found in the literature.

$$P_{\mathrm{crit}} = \frac{2 \cdot \pi \cdot b \cdot c \cdot \tau_{\mathrm{crit}}}{C^{*} \cdot K_{\mathrm{max}}} \quad [N], \tag{1}$$

where

b is the radius of the cylindric area filled by the potting compound [m],

c is the thickness of the core [m],

τ_{crit} is the critical shear stress of the core [Pa],

C^{*}, K_{max} are the dimensionless coefficients.

For more detailed description of the calculation, see [6]. Apart from this analytical calculation, it is possible to make a prediction using numerical methods such as the finite element method, see for example [7, 8]. Numerical calculations cannot replace experimental testing, but they can help us to understand the stress distribution in the vicinity of the insert and describe the development of individual failure modes leading to the final fracture.

3. The proposal for the 3D printed potted insert

The design of potted inserts has been carried out with regard to mechanical and thermal resistance, optimum shape of the distribution channels, and as low a mass as possible. The position of the channels has been carefully selected to ensure an even distribution of the potting compound and the shape and size of the channels has been designed to maximise the flow of the compound without reducing the strenght of the insert itself. Insert printing was performed using CreatBot F430 3D Printer, which allows the use of high melting temperature plastics, such as Polyetheretherketone (PEEK) or polyetherimide (PEI). PEEK was intended as the final material of the potted inserts thanks to its very good thermal and mechanical resistance and low outgassing when used in high vacuum applications. PEI has been considered as well, but it has worse mechanical properties than PEEK and is more dificult to 3D print as well. Basic material properties of PEEK are as follows: specific mass is $1.32\,\mathrm{g\,m^{-3}}$, melting temperature is 340 °C, and tensile strength is around 100 MPa.

Figure 2. The arrangement of the pull-out test [6].

The proposed insert has a star shape. The main idea was to maximise the interface area between the insert and the potting compound at a minimal insert volume to minimise its mass, thus the shape converged to the star. This shape was similar for all development options. A higher interface area increases the load bearing capacity of the bonded joint. The inner structure was designed with respect to potting compound distribution channels. These channels also have a deaeration function and indicate the sufficient amount of the potting compound. The traditional cylindrical insert is fitted into the cylindrical cavity machined into a panel, where the star insert is fitted into a star shaped cavity, thus increasing the load bearing area.

The screw thread cannot be printed directly as a part of the insert. Therefore, the thermal pressed insert Simaf 40/TH060H090 with the inner screw thread M6 was used. The threated insert is installed by hot pressing. The final design including the threaded insert is presented in Figure 3 and the 3D printed inserts of the final design made of PEEK thermoplastic are shown in Figure 4.

The mounting hole in the sandwich panel must be CNC machined to match the shape of the insert. The hole machining is shown in Figure 5a, and a detail of the final hole is shown on Figure 5b.

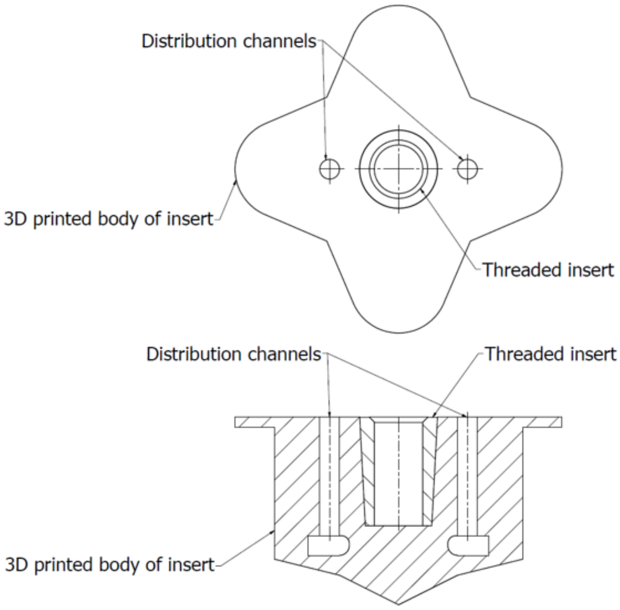
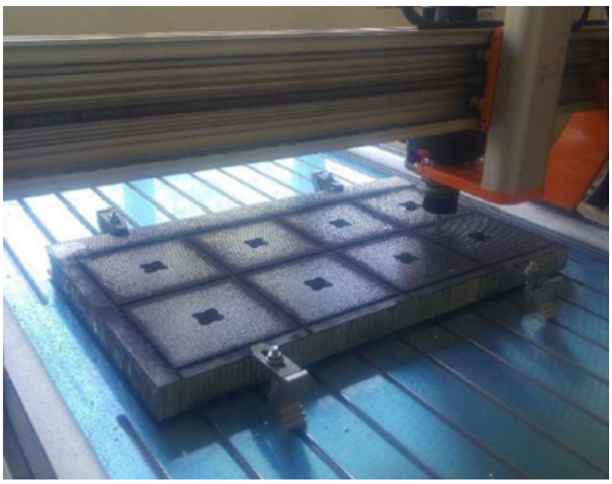


Figure 3. The shape of the proposed potted insert with the basic description.

Figure 4. 3D Printed inserts of the final design.



(a). Machining of the holes in sandwich panel.

(b). Detail of the final hole.

Figure 5. Machining of the holes and detail of the final hole.

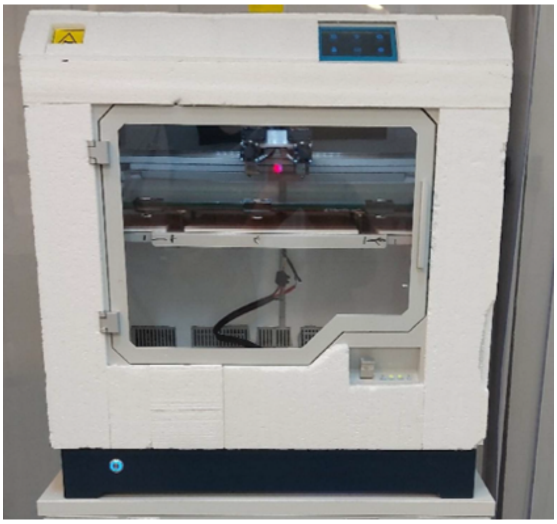


Figure 6. CreatBot F430 3D Printer with the outer insulation.

4. Production tests

Production tests were performed in terms of two main aspects. The first was to test the 3D printing process and evaluate the quality of the printed insert. The calibration of the printing process was necessary due to the use of PEEK, which is difficult to print with. The second aspect was the evaluation of the fitting and potting process. The fitting and potting process are key parameters that affect the final properties of the potted insert. Installation time is also important from a financial point of view.

The quality of printed inserts was improved in several steps. Based on the manufacturer description, the CreatBot F430 3D Printer should be able to print thermoplastics with a melting temperature over 350 °C. The reality was different, and it was necessary to perform printer modifications. The most significant problem was finding the optimum temperatures of the nozzle, built platform, and inner space of the printer. Also, the cooling process of the printed part is a key parameter in the case of PEEK printing and requires a good control of the inner temperature of the printer. If these parameters are inappropriate, printed parts are prone to delamination of layers and peeling of the parts from the built platform. To reach the optimum temperatures and their control, it was necessary to thermally insulate the printer, see Figure 6. The insulation ensures that the internal temperature of the printer is less dependent on the external temperature. Also, the original settings of the heated built platform were changed. To ensure a good temperature shape stability, the built platform was equipped by a glass plate. The temperature of the build platform was kept between 80 °C and 100 °C. This temperature range ensures a good adhesion between individual layers of the built part. It is possible to print parts of heigh up to 20 mm because as the distance from the heated build platform increases, the temperature of the growing part rapidly decreases.

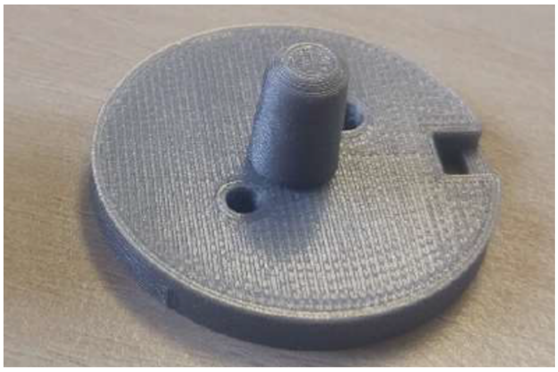


Figure 7. The jig used for the fixation of the insert.

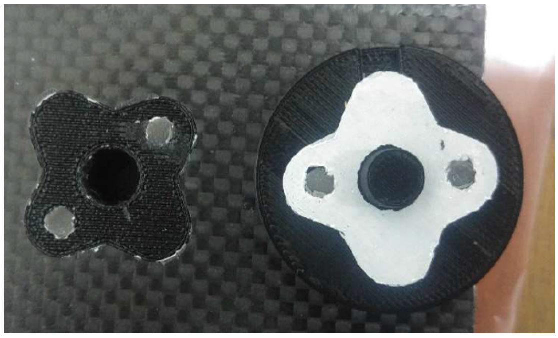


Figure 8. Insert after the installation with the use of adhesive tape.

In addition, the temperature of the nozzle was measured and calibrated to the optimum value. A nozzle temperature lower than 370 °C is too low and the material does not melt enough. A nozzle temperature over 395 °C is too high and causes problems, such as melting the printed parts in the vicinity of the nozzle. This is significant for parts with small details that can be easily damaged by melting.

From a fitting and potting process point of view, the optimisation was performed mainly to improve the repeatability of the properties of potted inserts and in order to reduce the fitting time. For fitting commercially available potted inserts, the fitting tab is used to fix the insert in the proper position. During the development of inserts discussed in this paper, several installation methods were tested. The simplest one was to pot the insert without any fixation. This method caused problems with the precision of fitting and sinking the insert too deep into the hole. Therefore, a jig for a better fixation of the insert was designed, see Figure 7. This jig ensures a perpendicular position of the insert to the sandwich panel. In addition, it prevents the insert sinking too deep into the hole. This is caused by the unwanted force exerted by the injection tool when injecting the compound manually. When using the jig, this force is absorbed by the jig. Contrary expectations, this problem was only partially eliminated. The sinking of the insert was not as significant, but was still observed.

In another step, the jig was bonded together with the insert using an adhesive tape, see Figure 8. This

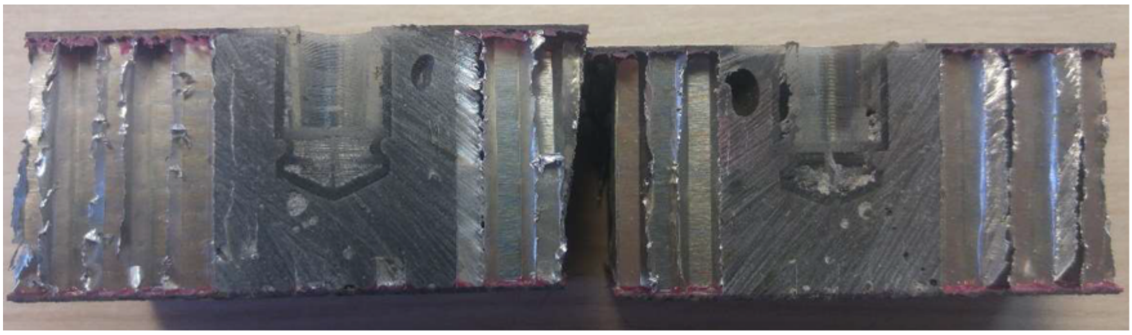


FIGURE 9. The cross-section of the panel with the insert fixed by the potting compound.

Test Specimen	Maximal Force [kN]
V43b – 1	2.333
V43b – 2	1.727
V43b – 3	0.541
Mean	1.534
St. Deviation	0.912
Variation Coef. [%]	59.5

TABLE 1. The results of the pull-out tests of the proposed inserts.

method eliminated the sinking of the inserts into the panel and a very good fitting precision.

Visual investigation presented in Figure 9 is a destructive method and cannot be performed in the case of products intended for the market. In these cases, it is possible to perform the investigation using one of NDT methods, which are available, see e.g. [9].

5. Mechanical testing

The proposed insert was subjected to the pull-out test to determine the critical force. In this screening testing, only three test specimens were tested. The inserts submited to the mechanical tests were fitted with an M6 thread. The arrangement of the pull-out test is shown in Figure 2. The loading velocity was 2 mm min^{-1}. The mean value of the critical force is 1.524 kN, see Table 1, which is in line with expectations. Nevertheless, the results are affected by a great scatter, and therefore the coefficient of variation reaches a value of 59.5 %. Such a high value is also caused by the low number of test specimens. Test specimens are shown in Figure 10. Standard potted inserts made from aluminium alloy were also tested for a comparison with proposed inserts. Inserts of a comparable size and with the same M6 thread were chosen. The same pull-out test arrangement and parametres were used. The mean value of the critical force for standard inserts is 3.38 kN, see Table 2. Test specimens after pull-out test are shown in Figure 11.

The failure mode of both types of inserts was different. The failure mode of the 3D printed inserts can be described as the failure of the adhesive joint between

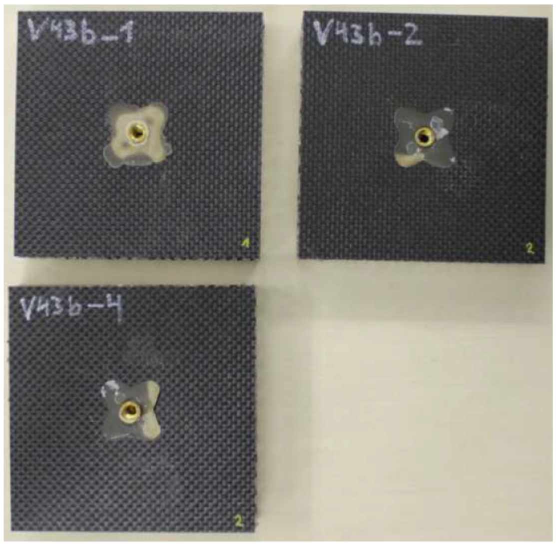


FIGURE 10. Test specimens after the tests.

Test Specimen	Maximal Force [kN]
V50 – 1	3.51
V50 – 2	3.35
V50 – 3	3.28
Mean	1.534
St. Deviation	0.912
Variation Coef. [%]	59.5

TABLE 2. The results of the pull-out tests of the standard inserts.

the insert surface and the potting compound. Bonding PEEK is known to be very complicated. The high coefficient of variation is caused by an uneven quality of the adhesive joint. There are two possibile ways to solve this problem. The first is to change the design and implement a form-fit connection into the insert. In this case, the critical force will not be dependent only on the quality of the joint. The second possibility is to perform surface treatment in order to improve the quality of the joint. The failure mode of the standard inserts is described as shear failure of the core at the edge of the potted area. This is possible due to the design of the body of the inserts, which enables form-fit connection with the poting compound.

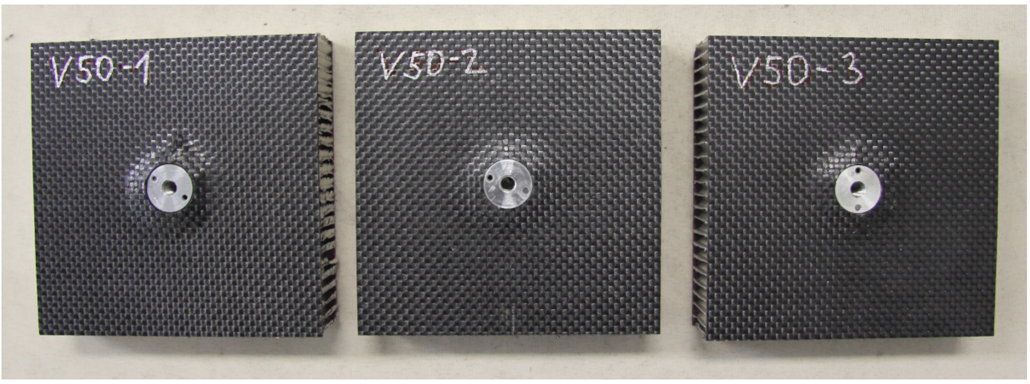


FIGURE 11. Standard potted inserts after the pull-out test. Deformation of the skin is caused by the honeycomb shear failure.

6. Conclusion

The main objective of this paper is to present the development, manufacturing, and testing of plastic inserts for sandwich panels produced by Fused Deposition Modelling 3D printing technology. During production testing, a calibration of the printer settings was necessary in order to achieve satisfactory quality. Also, the potting process was improved using jigs which were designed for this purpose. As a result, the fitting can be carried out with sufficient precision.

During the development, some problems, which stem from the poor quality of the glued joints of PEEK inserts, were also encountered. A poor reliability of bonded joints is the main reason for the high scatter of the measured critical force. To solve this issue will be the main objective of a further research. The issue of the PEEK bonding is often the objective of research projects and has not yet been satisfactory solved to this day. Hovewer, the proposed inserts performed worse than the standard inserts used for the comparison. This is due to different failure mode occurring for each type of inserts. The proposed inserts suffered adhesion failure between the body of the insert and the poting compound, where the standard inserts failed by honeycomb shear at the interface with the poting compound. This is caused by the form-fit connection of the standard insert's bottom flange (see Figure 1). Further research and development of the proposed additively manufactured inserts is required address this issue, as well as design changes of the inserts are neccesery to include a form-fit connection and further optimise the inserts.

Acknowledgements

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