Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 29 (2019) 288–295

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

18th International Conference on Sheet Metal, SHEMET 2019

Joining by forming of lightweight sandwich composite panels

T.R.M. Contreiras[a], J.P.M. Pragana[a], I.M.F. Bragança[b], C.M.A. Silva[a], L.M. Alves[a], P.A.F. Martins[a],*

[1]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[2]ISEL, GI-MOSM, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Rua Conselheiro Emídio Navarro, 1959-007 Lisboa, Portugal

---

Abstract

This paper presents a new joining by forming process to assemble longitudinally two metal-polymer sandwich composite panels perpendicular to one another. The process combines sheet-bulk forming with mortise-and-tenon joints to produce mechanically interlocked joints with large and stiff flat-shaped heads. Experimentation and finite element modelling with representative unit cells give support to the presentation and special emphasis is placed on the application of the process to the fabrication of lightweight composite panels for structural applications. Failure of the joints takes place by cracking and not by disassembling after unbending the flat-shaped head of the joint back to its original shape. The required forces to produce the new type of joints are below 15 kN, allowing them to be an easy to implement alternative to existing solutions based on adhesives or fasteners.

Keywords: Joining by forming; Sandwich composites; Lightweight panels; Experimentation; Finite element method

---

1. Introduction

In the last years there has been a growing interest in the utilization of lightweight sandwich composites for applications requiring a combination of high structural rigidity, low weight and thermal, noise and/or vibration

---

* Corresponding author. Tel.: +351 21 8419006
E-mail address: pmartins@tecnico.ulisboa.pt

10.1016/j.promfg.2019.02.140

insulation. The range of applications is wide, spanning from civil engineering structures to floor and side panels of transportation vehicles.

The automotive industry has been particularly interested in metal-polymer sandwich composites to make lighter, safer and more fuel-efficient vehicles. A metal-polymer sandwich composite is typically made of three layers consisting of a thick low-density polymer core and two thin metal sheets bonded to each side of the core. In case of steel-polymer sandwich composites that will be the focus of this paper, potential applications in automotive encompass a wide variety of parts such as the roof, hood, fenders, doors and floor panels [1]. This explains the reason why research in metal-polymer sandwich composites has been mainly focused on forming [2, 3] and joining processes [4].

Despite the above mentioned advantages, the use of steel-polymer sandwich composites in automotive has been limited because of the costs associated with the materials and processes, namely to the necessity of joining the parts made from sandwich composites with the adjoining components and body-in-white structure. The applications in aircrafts, ships and trains [5] have also been limited by the same type of difficulties. The conclusion is that there is a need to develop new, less expensive, joining processes to make the use of metal-polymer sandwich composites more affordable and widespread in industry.

The existing processes for joining two metal-polymer sandwich composites can be classified into three different groups: adhesive bonding, mechanical fastening and joining by forming (Fig. 1) [6, 7].

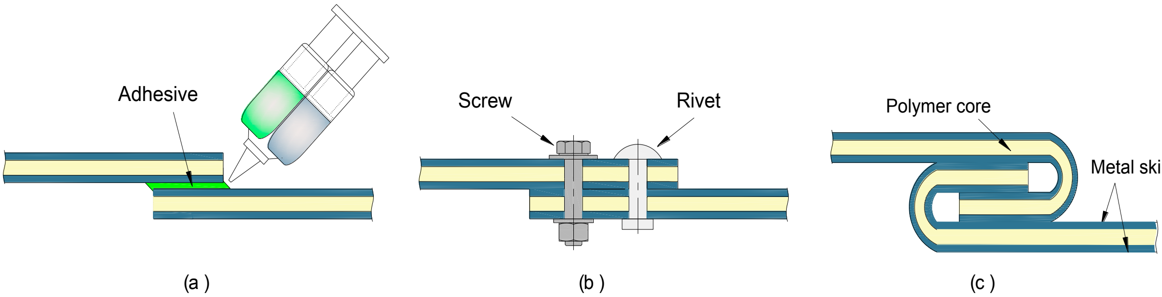


Fig. 1. Current processes for joining metal-polymer composite sandwiches. (a) Adhesive bonding; (b) Mechanical fastening (e.g. screws and nuts) and (c) Joining by forming (e.g. hemming/seaming).

Adhesive bonding (Fig. 1a) is a well-known process that requires surface preparation, application and curing of the adhesives at room or elevated temperatures [8]. During curing, clamps, jigs and fixtures are used to lock and hold the metal-polymer sandwich composites in position and to ensure a uniform application of pressure. Major drawbacks are surface preparation, long curing times and sensitivity to service temperature, applied stresses and fluids. Disassemble of adhesive bonded joints is also difficult.

Mechanical fastening (Fig. 1b) is the leading process for joining metal-polymer sandwich composites. The use of screws and rivets is widespread in transportation vehicles [9] and the resulting joints are easily assembled and disassembled without damaging the sandwich composites. However, mechanically fastened joints subject the sandwich composites to concentrated stresses, their performance is dependent on the maximum service load that screws and rivets can safely withstand and are sensitive to creeping under the influence of thermal stresses. In addition, mechanical fastening increases the overall weight of the structures by the use of screws and/or rivets.

Application of joining by forming to metal-polymer sandwich composites is nowadays limited to table-top hemming (machine hemming) and roller hemming (Fig. 1c). Both processes are state-of-the-art solutions that have been successfully applied in automotive door outer panels [1] but their industrialization is complex and costly, preventing its use in small batch applications.

Under these circumstances, the main objective of this paper is to present a new joining by forming process to assemble longitudinally in position two metal-polymer sandwich composite panels perpendicular to one another. The concept draws from earlier developments of the authors for metal [10] and polymer [11] sheets, and envisages a new solution based on a multi-stage sheet-bulk forming [12] sequence that is specially designed for sandwich composites. The process is capable of producing mechanically locked joints with good pull-out forces and an example is given to prove its adequacy for assembling floor or side panels for structural applications.

2. Experimentation

2.1. Stress-strain curves

The development of the new proposed joining by forming processes was performed with litecor sandwich composite panels supplied by ThyssenKrupp. The panels had a thickness $t_0 = 2$ mm and consisted of a polymer core layer (1 mm) made of a mixture of polyamide and polyethylene and two thin metal sheets (0.5 mm) made of an interstitial free steel bonded to each side.

The stress-strain curves of the polymer core and of the steel sheets were determined by means of stack compression tests, which allowed obtaining the stress response of both materials for large values of strain, namely for those beyond necking in tension [13] (Fig. 2). Tension tests were not performed for the complete characterization of the strength differential effect of the polymer core because the main acting stresses in joining by forming are compressive.

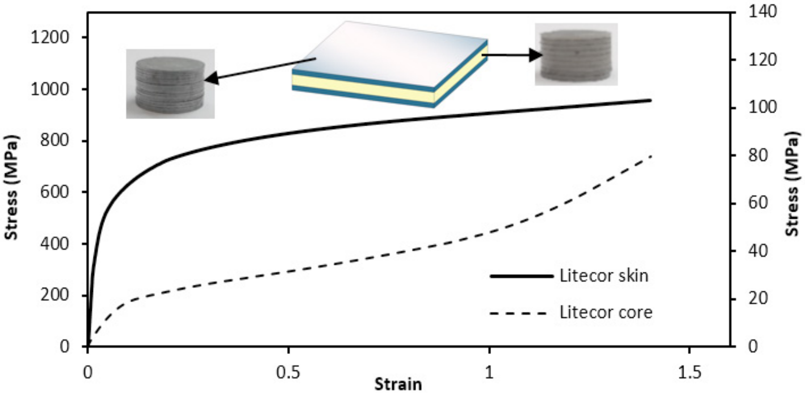


Fig. 2. True stress-strain curves of the skin and core materials of the litecor sandwich composite panels. Note: The left vertical axis applies for the skin (steel) and the right vertical axis applies for the core (polymer) materials.

The stack compression tests were carried out at room temperature in a hydraulic testing machine with a cross-head speed equal to 10 mm/min and the specimens were assembled by piling up circular discs cut out from the two different layers of the sandwich composite panels.

2.2. New joining by forming process

The new proposed joining by forming process is shown in Fig. 3c and is made of three different stages. In the first stage, the polymer core of the tenon placed above the surface of the mortise is removed with a small cutting tool having a straight cutting edge. The second and third stages perform the nosing and the flat punch upsetting of the outer thin metal sheets of the tenon. The goal is to produce a flat-shaped head with a compression bead in order to increase the overall strength of the joint, as will be shown later in the paper.

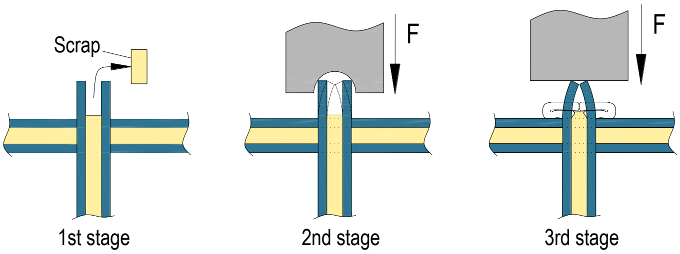


Fig. 3. The three different stages (cutting, nosing and upset compression of the tenon) of the new proposed joining by forming process to assemble longitudinally two metal-polymer sandwich composite panels perpendicular to one another.

The development of the new proposed joining by forming processes was carried out in ‘representative unit cells’ that replicate the mortise-and-tenon joints utilized for fixing longitudinally in position two sandwich composite panels perpendicular to one another. The ‘representative unit cell’ concept had already been used by the authors in a previous experimental work on tee joints made from metal and polymer sheets perpendicular to one another [10], [11] and in lap joints made from metal sheets in which one sheet is partially placed over another [14].

The typical ‘representative unit cell’ utilized in this work is made of a small sample with a tenon, which is wider than longer and another small sample with a mortise consisting of a rectangular through-thickness hole (Fig. 4). The ‘representative unit cells’ were cut-out from the supplied litecor sandwich composite panels by water jet.

t_0 (mm)	w_0 (mm)	l_0 (mm)
2	10	2 to 5

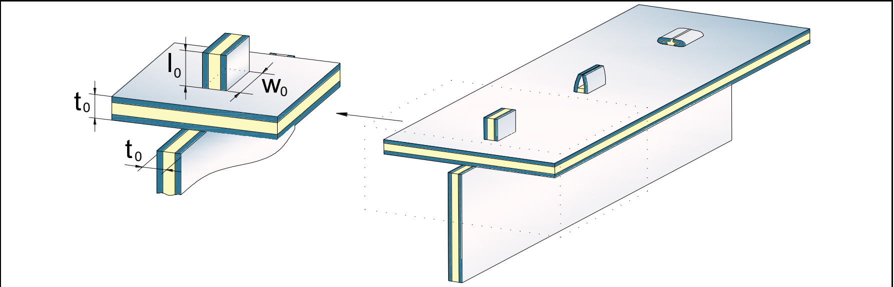


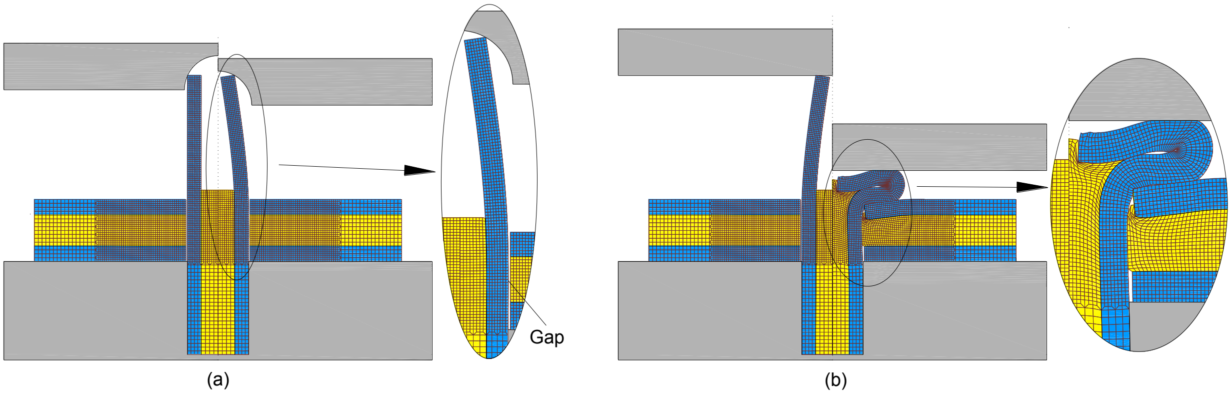
Fig. 4. Representative unit cell with the geometries of the tenons and mortises that were utilized in the experiments.

Fig. 4 summarizes the geometry and dimensions of the mortises and tenons that were utilized in the experiments. As seen, only the free length l_0 of the tenon was allowed to vary because the width w_0 and thickness t_0 of the tenons were kept unchanged. The lack of influence of width w_0 results from near-plane strain material deformation conditions and allowed decreasing the total number of experiments and focusing the investigation on the most critical parameter regarding workability and feasibility of the new joining by forming process.

3. Numerical modelling

The experiments were carried out at room temperature under a very small displacement rate of the cross head speed of the mechanical testing machine. The absence of inertial effects allowed numerical modelling of the new joining by forming process to be performed with an in-house computer program built upon the quasi-static finite element flow formulation.

The numerical simulation made use of two-dimensional plane strain deformation models. The cross-section of the sandwich composite panels was discretized by means of quadrilateral elements and the tools were modelled as rigid objects with their geometries discretized by means of linear contact-friction elements (Fig. 5).



(a) (b)

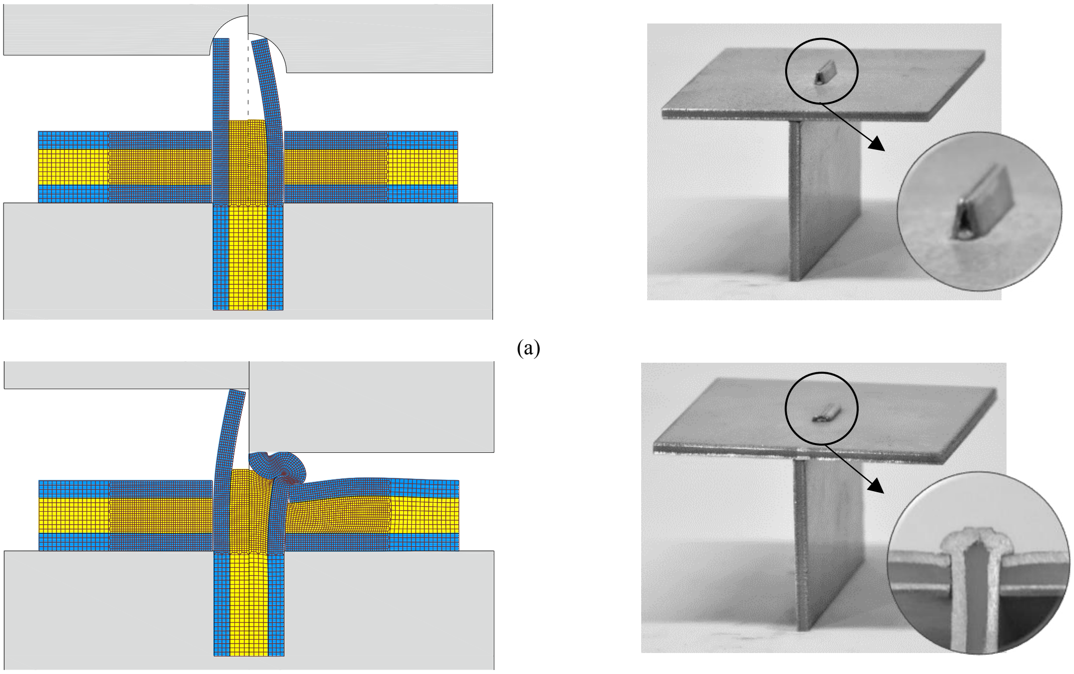
Fig. 5. Finite element simulation of the (a) second and (b) third stages of the new joining by forming process ($l_0 = 4$ mm).

A detailed description of the implementation of the finite element flow formulation in the computer program i-form utilized by the authors, with special emphasis on the numerical treatment of the contact with friction between deformable objects and between deformable and rigid objects is given by Nielsen et al. [15].

4. Results and discussion

4.1. Joining the representative unit cells

Fig. 6 shows the computed and experimental geometries of the representative unit cells at the end of the second (nosing) and third stages (flat punch upsetting) of the new joining by forming process. The process ensures the formation of mechanical joints with large flat-shaped heads for fixing longitudinally the two metal-polymer sandwich composite panels perpendicular to one another.



(a)

(b)

Fig. 6. Assembling two sandwich composite panels perpendicular to one another by means of the new joining by forming process. (a) Finite element predicted cross section and photograph of a joint at the beginning and end of the second stage ($l_0 = 2.5$ mm); (b) Finite element predicted cross section and photograph of a joint at the beginning and end of the third stage ($l_0 = 2.5$ mm).

The final cross-sectional shape of the joint resembles that of a mechanical lock with a cotter pin. The final size of the flat-shaped head is directly influenced by the initial free length l_0 of the tenon, as can be observed by comparing the finite element results for $l_0 = 4$ mm (Fig. 5) and $l_0 = 2.5$ mm (Fig. 6). In fact, the new joining by forming process takes advantage of plastic instability to produce large compression beads and, therefore, large flat-shaped heads instead of being limited by any sort of difficulties related to plastic instability, The metal reinforcement of the flat-shaped heads caused by metal folding over itself (compression beads) contributes to increase the overall strength of the joint and the pull-out forces that are required to detach the two sheets.

The evolution of the force with displacement in Fig. 7 allows distinguishing between the monotonic growth under small applied forces of the first stage (nosing) and the two region trend of the second stage (upset compression). In case of the later, it is worth mentioning the steep increase of the force as the flat-shaped head of the tenon is subjected against the lower sandwich composite panel containing the mortise. Still, the maximum force per representative unit cell is below 15 kN allowing the process to be easily performed with low cost equipment.

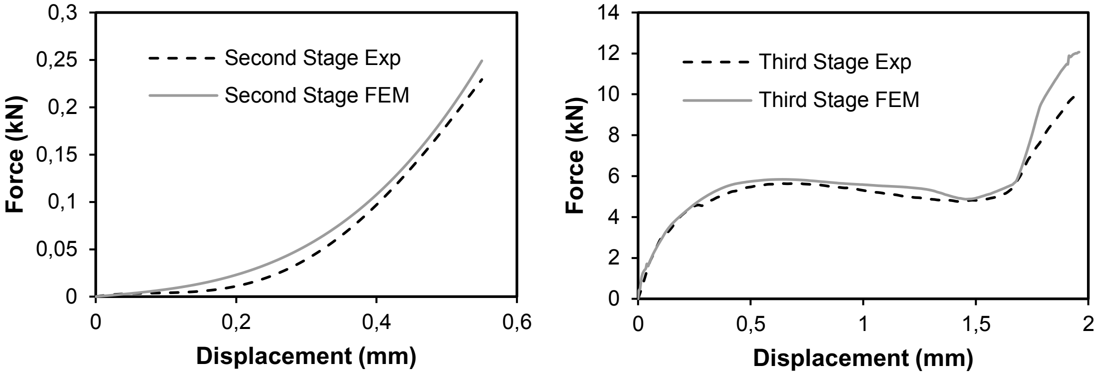
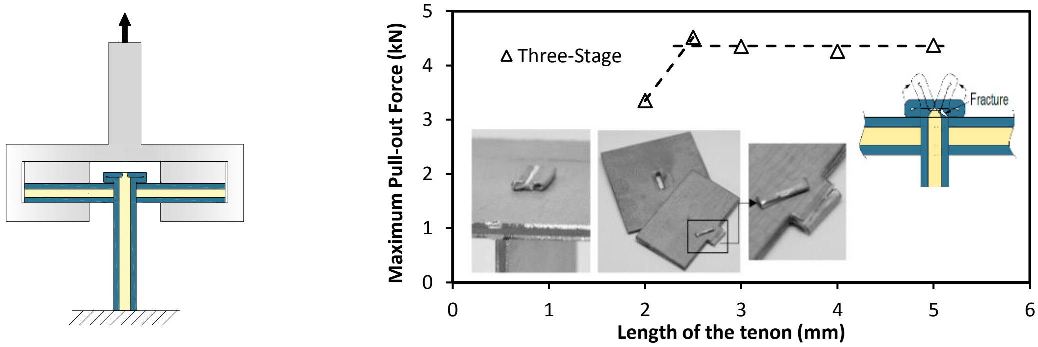


Fig. 7. Evolution of the experimental and finite element predicted force with displacement for the second and third stages of the new joining by forming process shown in Fig. 6 ($l_0 = 2.5$ mm).

4.2. Pull-out tests of the representative unit cells

The overall performance of the new joining by forming process was assessed by means of destructive pull-out tests aimed at determining the maximum force that the representative unit cells are capable to withstand before failure. The tests were carried out for the entire set of experimental conditions listed in Fig. 4.



(a)

(b)

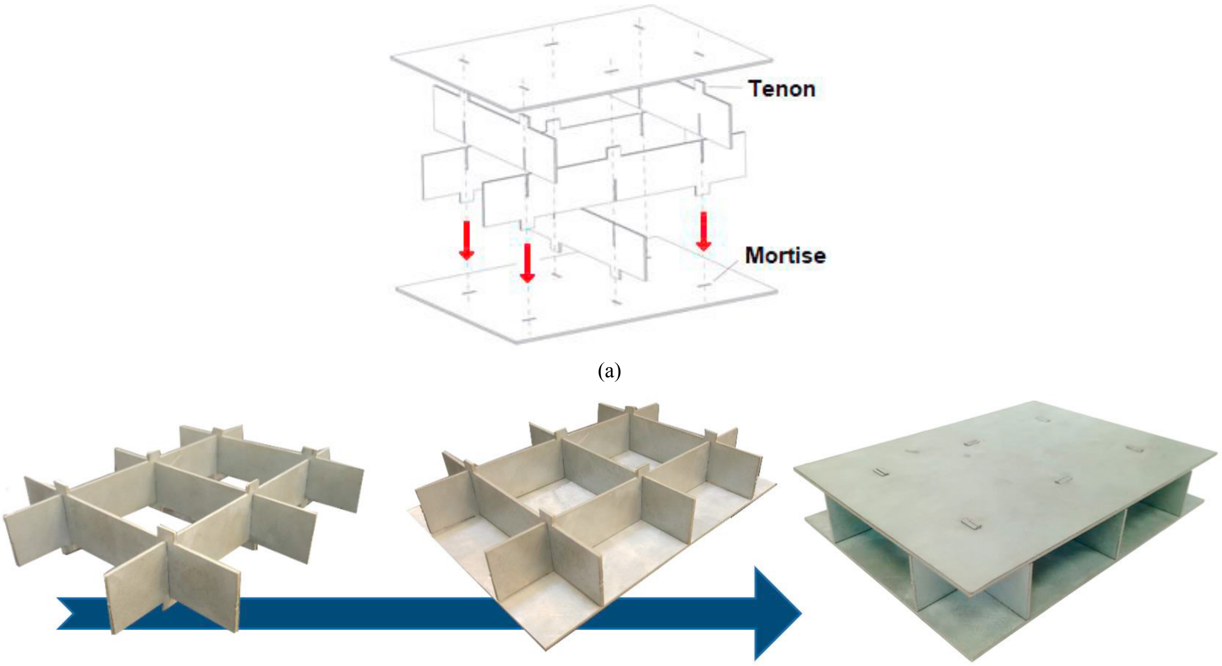
Fig. 8. Destructive pull-out tests of the joints produced by the new joining by forming process. (a) Schematic representation of the experimental setup and (b) maximum pull-out forces as a function of the free length l_0 with a photograph of a joint before and after testing;

The pull-out testing setup is schematically illustrated in Fig. 8a and the results of the experiments are included in Fig. 8b. It is interesting to observe that the pull-out forces increases with the length l_0 of the tenon up to a maximum value beyond which the force remains approximately constant due to the formation of large and stiff symmetric flat-shaped heads that fail by cracking (Fig. 8b). In fact, only the joint with $l_0 = 2$ mm fail by disassembling after unbending the flat-shaped head back to the longitudinal axis of the tenon.

4.3. Application to the fabrication of lightweight structural panels

This last section of the paper includes the application of the new joining by forming process to the assembly of lightweight structural panels made from a series of representative unit cells. The exploded view of Fig. 9a shows the various parts, namely the location and orientation of the different tenons and mortises that were utilized to fabricate the panel. As seen, tenons and mortises were orientated along two different directions in order to prevent preferential deformation in a given direction.

Fig. 9b shows the real panel at two different intermediate stages of assembly and after being produced.



(a)

(b)

Fig. 9. Application of the new joining by forming process to the fabrication of lightweight structural panels. (a) Exploded view of the panel and (b) photographs showing the real panel at different stages of assembly.

5. Conclusions

This paper presents a new joining by forming process to assemble longitudinally in position two metal-polymer sandwich composite panels perpendicular to one another. The process is performed in three different stages comprising, cutting out the polymer core of the tenon placed above the surface of the mortise, and mechanical interlock by nosing and flat punch upsetting of the outer thin metal sheets of the tenon. The resulting joints have large and stiff flat-shaped heads and their cross-sections resemble that of a mechanical lock with a cotter pin.

Representative unit cells of the joints can withstand pull-out forces of approximately 4.5 kN and fail by cracking of the flat-shaped heads instead of being disassembled after unbending the flat-shaped heads back to the longitudinal axis of the tenon.

Despite being reinforced with metallic compression beads, the representative unit cells assembled by the new joining by forming process still require less than 15 kN to be produced. This makes the process an effective, inexpensive, solution for assembling lightweight sandwich composites with portable equipment and also makes the utilization of these materials more affordable and widespread in industry. The fabrication of structural panels for civil engineering and transportation vehicles with design requirements of thermal, noise and vibration insulation are good examples of application of the new joining by forming process.

Acknowledgements

The authors would like to acknowledge the support of Fundação para a Ciência e a Tecnologia of Portugal under LAETA - UID/EMS/50022/2013 and PDTC/EMS-TEC/0626/2014 and the support provided by ThyssenKrupp Steel

Europe AG and Dr. Azeddine Chergui. The support provided by Instituto Politécnico de Lisboa under IPL/2016/CompSBJ_ISEL is also acknowledged.

References

[1] A. Grüneklee (Editor), The project ThyssenKrupp InCar plus, ATZ Extra, Wiesbaden: Springer-Verlag, (2014).

[2] M. Fazlollahi, M.R. Morovvati, B.M. Dariani, Theoretical, numerical and experimental investigation of hydro-mechanical deep drawing of steel/polymer/steel sandwich sheets, Journal of Engineering Manufacture, (2018) doi: 10.1177/0954405418780173 .

[3] D. K. Leu, Numerical and experimental studies of single-stroke bumper forming using high-strength steel and laminate sheets, Journal of Engineering Manufacture, 230 (2016) 1317-1330.

[4] W. Zhang, A. Chergui, C. V. Nielsen, Process simulation of resistance weld bonding and automotive light-weight materials, 7th International Seminar on Advances in Resistance Welding, Bosan, Korea, (2012).

[5] J. R. Vinson, Sandwich structures: Past, present and future, 7th International Conference on Sandwich Structures, Aalborg, Denmark, (2005) 3-12.

[6] S. T. Amancio-Filho, J. F. Santos, Joining of polymers and polymer-metal hybrid structures: Recent developments and trends, Polymer Engineering and Science, 49 (2009) 1461-1476.

[7] K. Mori, N. Bay, L. Fratini, F. Micari, A. E. Tekkaya, Joining by plastic deformation, CIRP Annals - Manufacturing Technology, 62 (2013) 673–694.

[8] D. A. Dillard, Advances in structural adhesive bonding, Cambridge: Woodhead Publishing, (2010).

[9] R. W. Messler, Trends in key joining technologies for the twenty- first century, Assembly Automation, 20 (2000) 118-128.

[10] I. M. F. Bragança, C. M. A. Silva, L. M. Alves, P. A. F. Martins, Joining sheets perpendicular to one other by sheet-bulk metal forming, International Journal of Advanced Manufacturing Technology, 89 (2017) 77–86.

[11] I. M. F. Bragança, C. M. A. Silva, L. M. Alves, P. A. F. Martins, Lightweight joining of polymer and polymer-metal sheets by sheet-bulk forming, Journal of Cleaner Production, 145 (2017) 98-104.

[12] M. Merklein, J. M. Allwood, B. A. Behrens, A. Brosius, H. Hagenah, K. Kuzman, K. Mori, A. E. Tekkaya, A. Weckenmann, Bulk forming of sheet metal, CIRP Annals - Manufacturing Technology, 61 (2012) 725–745.

[13] L.M. Alves, C.V. Nielsen, P.A.F. Martins, Revisiting the fundamentals and capabilities of the stack compression test, Experimental Mechanics, 51 (2011) 1565–1572.

[14] D.F.M. Silva, I.M.F. Bragança, C.M.A. Silva, L.M. Alves, P.A.F Martins. Joining by forming of additive manufactured mortise-and-tenon joints, Journal of Engineering Manufacture, (2017) https://doi.org/10.1177/0954405417720954

[15] C.V. Nielsen, W. Zhang, L.M. Alves, N. Bay, P.A.F. Martins, Modelling of thermo-electro-mechanical manufacturing processes with applications in metal forming and resistance welding, London: Springer-Verlag, (2013).