COMPRESSION MOULDING OF THERMOPLASTIC COMPOSITE SANDWICH COMPONENTS

Lance D. McGarva and B. Tomas Åström

Department of Aeronautics, Kungl Tekniska Högskolan (KTH)
SE-100 44 Stockholm, Sweden

SUMMARY: The manufacturing of sandwich components from pre-consolidated glass/polyamide 12 faces and polymethacrylimide foam core by compression moulding is studied. The influence of face temperature and moulding pressure on the mechanical properties of the face–core interface were characterised in terms of fracture toughness and shear strength, evaluated using a modified double cantilever beam test and shear test. A method of integrating a recycled glass/polyamide 12 full-core insert into a sandwich component at the time of moulding is studied and found to produce structurally capable inserts. The influence of insertion temperature on the transverse tensile strength of the insert is investigated and characterized using a pull-out test. Owing to the non-linear geometrical and material behavior of the specimens observed during pull-out testing and possibly also increased fracture resistance around the insert owing to core densification, higher strength specimens failed by core shear at some distance from the insert.

KEYWORDS: Thermoplastic, sandwich, manufacturing, compression moulding, inserts, mechanical properties

INTRODUCTION

The structural sandwich concept is an attractive option for applications requiring high specific bending stiffness and strength, high specific energy absorption, and good thermal and acoustic insulation properties. However, applications involving large production volumes, in the automotive industry for instance, generally preclude the use of traditional thermoset sandwich construction owing to time consuming and labour intensive manufacturing techniques. Thermoplastic sandwich construction, however, may be a suitable alternative. Thermoplastic sandwich components can be compression moulded with cycle times in the order of fractions of a minute [1-3] and the process is amenable to automation.

The sandwich concept relies on adequate shear strength of the face–core interface and face–core bonding is therefore of particular interest. The influence of the main independent process parameters on the mechanical properties of the interface is investigated for compression moulding glass/polyamide 12 (PA12) faces and polymethacrylimide (PMI) foam core. The addition of pure PA12 film to supplement the amount of matrix available for bonding at the face–core interface is also discussed.

Moreover, the issue of load introduction into sandwich constructions is addressed and a technique is described for integrating full-core inserts into a component at the time of moulding. The thermoplastic inserts contain recycled face laminates and are therefore short glass fibre reinforced. The influence of insert temperature during processing on insert pull-out strength is investigated.

COMPONENT MANUFACTURING

Components are manufactured by heating two pre-consolidated face laminates in an infra-red oven to a temperature exceeding the melt temperature of the matrix. The amount of matrix on the surface of the faces available for bonding is limited, therefore a bonding film of pure matrix material may be placed on the top surface of each laminate before heating. The heated faces are placed on either side of the core, the stack is quickly transported to the press and put into the lower mould half. The cooled mould closes rapidly and applies moulding pressure to re-consolidate the face laminates and bond them to the core. The mould then opens and the cooled component is removed.

Moulding pressure forces melted matrix available on the surface of the face laminates to flow into the open cells on the core surface (see Fig. 1), and upon solidification mechanically locks the faces to the core [4]. It is assumed that little or no chemical bonding occurs and interfacial bonding is governed by matrix penetrating into the core cells.

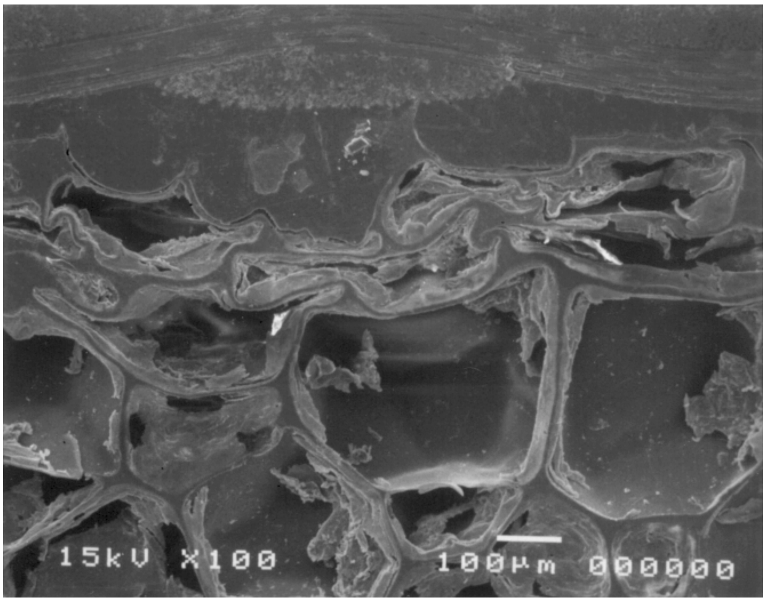

Fig. 1: Face–core interface showing surface cells filled with matrix and densified core cells

After coming into contact with the heated faces, the core structure near the interface is heated, therefore reducing its yield strength. Moulding pressure then, in addition to forcing matrix available on the surface of the faces to flow into the open cells on the core surface, partly or totally collapses the walls of cells near the core surface as shown in Fig. 1. As expected, increasing face temperature or moulding pressure increases the depth and degree of core densification and thus reduces the overall panel thickness.

Sandwich panels manufactured for this study consisted of 10 mm thick Rohacell 110 IG and 0.8 mm thick pre-consolidated face laminates containing four layers of Vestopreg G 101 with the addition of 0.1 mm thick Vestamid L1600 bonding film. A 40 mm wide, 0.05 mm thick polytetrafluoroethylene (PTFE) film was placed along one side of the panel between face and core during manufacture, serving as a controlled starter crack for the modified double cantilever beam (DCB) test specimens. Mould temperature, forming rate, and moulding time were set to 23°C, 1 mm/s, and 10 s respectively.

Three panels were manufactured using each set of process parameters in the main area of interest (see Table 1). Additional sets of process parameters outside the main range of interest (shown in brackets) were used to manufacture one panel each. Two of each specimen type to be tested were cut from each panel. The face temperature given in bold-face was used to manufacture all panels where moulding pressure was varied and vice versa.

Table 1: Compression moulding process variables

Process Variable	Setting					
Face temperature (°C)	189	203	**225**	240	(255)	(279)
Moulding press. (MPa)		0.25	**0.75**	1.0	1.25	(1.75)

INSERT INTEGRATION

A method has been developed for including a full core insert in a compression moulded sandwich component. The insert is heated around its periphery, concurrently with heating the face laminates. Just prior to compression moulding the component, the partly melted insert is pressed into a pre-machined hole in the core. Insertion force makes the molten insert material flow, entirely filling the hole. Bonding is achieved by insert matrix filling the open cells on the inside surface of the hole under insertion force and subsequent moulding pressure, mechanically locking the insert into the core.

The core is then stacked between the two heated face laminates and compression moulded in the fashion described above. The insert conforms between, and bonds to, the face sheets under moulding pressure and melted matrix fills any voids or open cells on the surface of the hole not filled during insertion. Furthermore, the insert is of greater volume than the hole, and expands into the core material, densifying the cells around the hole. Densification has shown to have a beneficial effect on bonding thermoplastic matrix to PMI foam core [5].

MECHANICAL TESTING

Modified double cantilever beam test

The DCB test method was used to calculate critical strain energy release rate G_C as a function of crack length and is used to indicate the degree of face–core bonding. The method was based on ASTM D 5528 "Standard test method for mode I interlaminar fracture toughness of unidirectional fibre-reinforced polymer matrix composites". The modified beam theory (MBT) method was used for data reduction.

The 300 mm long by 30 mm wide DCB specimens were prepared by machining the ends containing the PTFE film to allow them to be held in the test fixture shown in Fig. 2. Hinges were adhesively bonded to the top faces to obtain an initial crack length of 12 mm. The loading arm was sufficiently long and hinged at the top to ensure that the load was applied to the specimen near vertically throughout the test, regardless of the large change in geometry owing to the thin and relatively compliant faces. The specimens were tested at a constant rate of 2 mm/min.

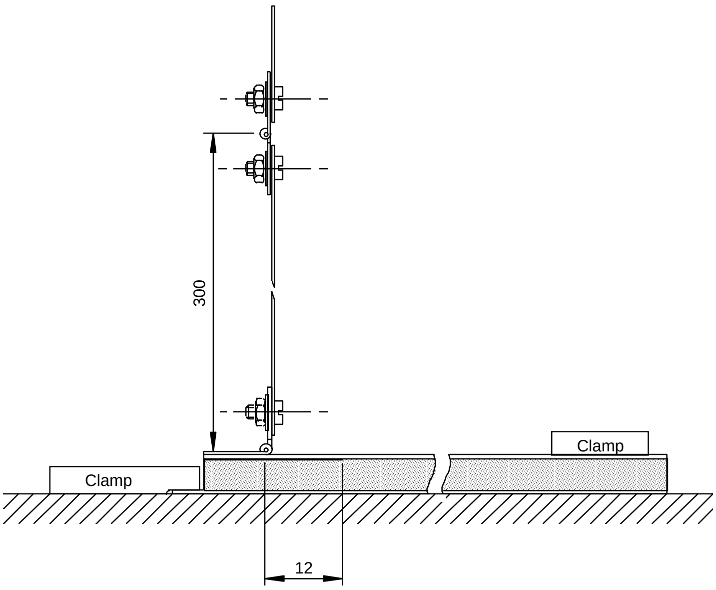

Fig. 2: Modified DCB test setup

Shear test

Shear tests were performed in accordance with ASTM C 273. The 150 mm long by 30 mm wide specimens were adhesively bonded to steel loading plates at least 30 mm thick. Shear strain was measured with an extensometer mounted between magnetic blocks on the loading plates.

Insert pull-out test

Pull-out tests were performed to evaluate the influence of process parameters on the transverse tensile strength of the inserts. In general, inserts are not well suited to carry moments and attachments should be designed to apply transverse (pull-out) and in-plane loads only. The transverse tensile strength is therefore considered suitable for characterizing insert strength.

Specimens are prepared for the test by cutting diameter 200 mm circular panels using a fine tooth bandsaw. A hole is drilled through the top face, down the center of the insert almost to the bottom face. A bracket is attached to the insert with a metallic fastener (6 mm outside diameter, 3 mm pitch) intended for thermoplastics, to allow being held in the test fixture illustrated in Fig. 3. All testing was performed using a constant rate of 2 mm/min.

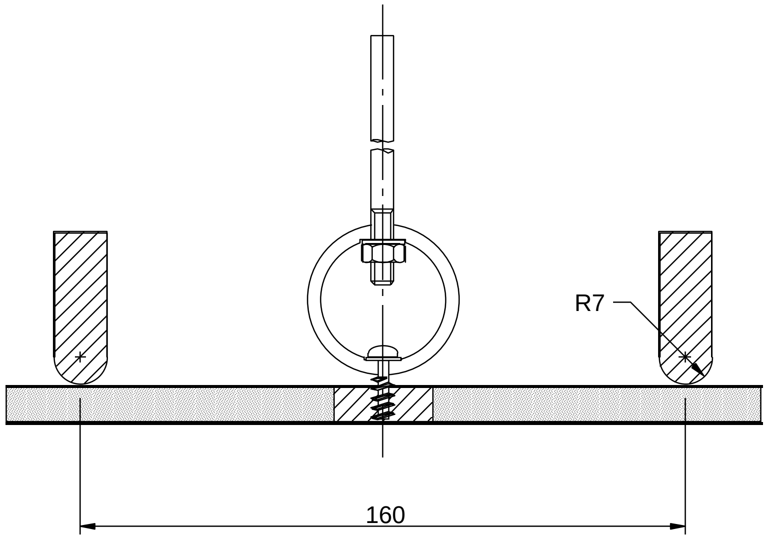

Fig. 3: Insert pull-out test setup

RESULTS AND DISCUSSION

The addition of a pure PA12 bonding film to supplement the matrix available at the face–core interface is required to completely fill the open cells on the core surface and significantly improves face–core bonding. Initial trials indicate more than a three fold average increase in bond strength with the addition of a 0.1 mm bonding film [5]. All specimens for this study were therefore manufactured with the addition of bonding film.

Interfacial toughness

Specimens manufactured with low moulding pressure failed by matrix on the face surface being partially or completely pulled out of the core surface cells it occupied. In all other cases the interfacial crack appears to propagate predominantly along the bottom of the partially or totally collapsed cells in the densified region of the core adjacent to the interface, which may more accurately be described as an interphase.

Increasing moulding pressure increases the depth and degree of damage to the softened cell walls near the interface. This densification clearly has a positive effect on G_C as Fig. 4 shows (in all figures, error bars indicate standard deviation). When a tensile load is applied to a cellular solid, cell walls become more aligned with the direction of loading, bending cell edges and stretching cell walls [6]. The buckled walls of the collapsed, densified core cells will allow a greater degree of cell edge bending and wall stretching than undeformed cells, therefore likely increasing the compliance of the core structure in the interphase.

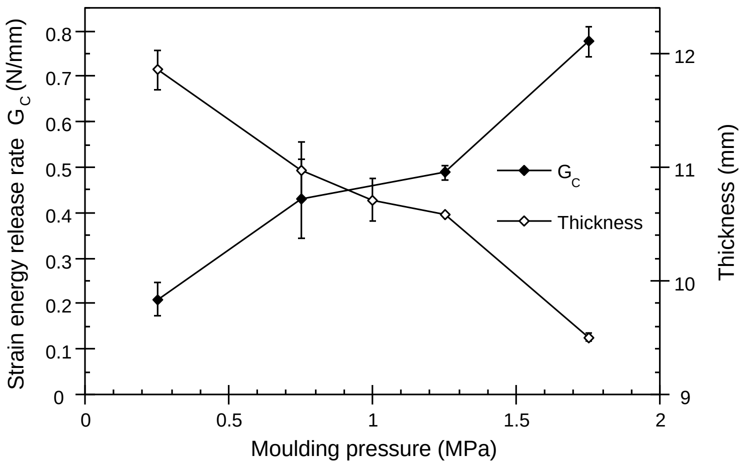

Fig. 4: Effect of moulding pressure on strain energy release rate

Increasing face temperature also increases core densification near the interface. This has a positive effect on G_C up to face temperatures near 240°C, as Fig. 5 shows. The initial mechanism here appears similar to that for increasing moulding pressure, where increasing densification of the core structure near the interface increases fracture resistance. However, at face temperatures above approximately 240°C the core structure appears to be affected in a different manner and G_C reduces. In addition to further densification, cell size appears to reduce, cell walls become thicker, and discolouration of the core material is observed, indicating chemical change and therefore a likely reduction in the fracture toughness of the core [5].

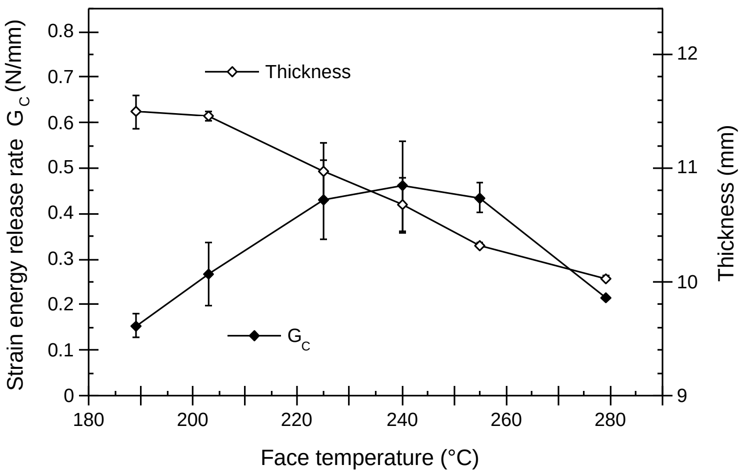

Fig. 5: Effect of face temperature on strain energy release rate

Shear strength

At low moulding pressures the shear strength of the sandwich appears to be determined by the strength of the interface, which is less than that of the core. The shear strength of the interface, and hence the sandwich, increases with moulding pressure up to approximately 1 MPa (see Fig. 6) where it equals the shear strength of the core material (≈ 2.4 MPa), which then determines the panel shear strength. Therefore, increasing the moulding pressure further has no effect on the shear strength of the panel and only continues to reduce the overall thickness.

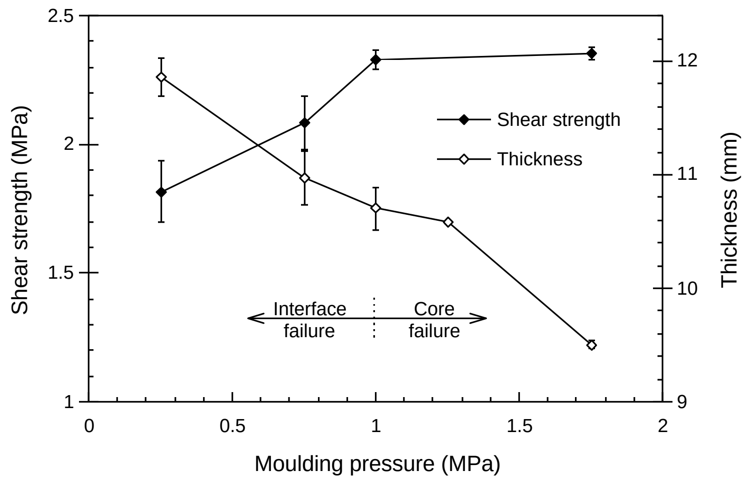

Fig. 6: Effect of moulding pressure on shear strength

Fig. 7 shows that as face temperature is increased, the shear strength of the interface increases rapidly to almost the shear strength of the core (Note that a moulding pressure of 0.75 MPa was used to manufacture all panels where face temperature was varied and as shown in Fig. 6 the highest shear strength achieved, i.e. the core shear strength, was not reached until the moulding pressure was increased to approximately 1 MPa). No improvement in panel shear strength is observed by increasing the face temperature further and excessive temperatures result in a reduction of panel shear strength, a reduction in panel thickness and increasing discolouration of the faces [5].

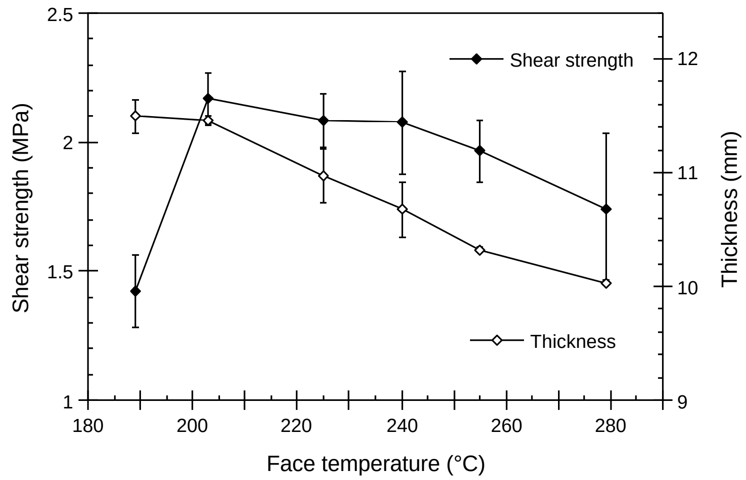

Fig. 7: Effect of face temperature on shear strength

Insert pull-out strength

Pull-out testing components to failure proves difficult owing to the high insert strengths achieved. It is not uncommon for the metallic fastener to pull out of the insert before component failure occurs. The 6 mm diameter metallic thermoplastic fastener pulls out of the insert at an average load of 3.9 kN with a standard deviation of 0.38 kN (given in parentheses in the following).

Only at low insert preheat temperatures, where little of the insert is melted, is the transverse tensile strength affected to any significant degree. Components manufactured with an insert center temperature of 40°C failed by face–insert debonding at an average load of 2.9 (0.44) kN. Components manufactured with an insert center temperature between 60°C and 180°C (completely melted) failed by pull-out of the fastener at an average load of 3.9 (0.38) kN.

It is possible to more reliably test the panels to failure using the described test method with the fastener threaded completely through the insert and out the back face of the specimen, although in practice this is considered undesirable. Other than the fastener pulling out of the insert, there appears to be two distinct failure modes; slow debonding of the bottom face–insert interface initiating from the outside and propagating inwards followed by rapid debonding and core shear failure from the lower three-material corner, or core shear failure a certain distance from the insert [7].

Large component deflections (12 mm) and distortion of the face laminates during testing induce considerable local bending and membrane stresses in the faces, altering the shear stress distribution in the core. If the face–insert bond strength is sufficiently high, the shear stress in the core reaches the core shear strength at some distance away from the insert and failure occurs. Failure loads of 5 kN were achieved. The fillet around the face–core interface on the insertion side formed during insert integration reduces the stress concentration in this area. Furthermore, the insert–core and face–core interfaces are likely toughened owing to core densification, which further reduces the likelihood of failure from the lower three-material corner [5, 7].

CONCLUSIONS

The addition of a pure PA12 film significantly improves face–core bonding by supplementing the matrix required to fill the open cells on the core surface.

Increasing moulding pressure increases the depth and degree of core densification near the interface, which has a positive effect on the shear strength and fracture toughness of the interface. Similar improvements in interfacial fracture toughness are observed for increasing face preheat temperature up to approximately 240°C wherefrom a negative effect is observed, likely due to degradation of the core material. Components manufactured with a moulding pressure of 1 MPa and face preheat temperature of 225°C have the maximum overall measured mechanical properties.

Insert pull-out tests result in large component deflections and core shear failure far from the insert, although it is not uncommon for the threaded metal fastener to pull out of the insert before component failure occurs. This indicates that the method of insert integration produces components with structurally very capable inserts.

ACKNOWLEDGEMENTS

This work was supported by the Commission of the European Union under Brite-EuRam contract number BRE2-CT94-0912. Helpful advice and discussions with Prof. D. Zenkert and M. Åkermo are gratefully acknowledged. K. F. Karlsson is acknowledged for initial development work on the method of insert integration. Vestopreg, Vestamid and the insert

material were supplied by Hüls, Marl, Germany, and Rohacell was supplied by Röhm, Darmstadt, Germany. Vestopreg face laminates were consolidated by Institut für Verbundwerkstoffe, University of Kaiserslautern, Germany.

REFERENCES

1. Åkermo, M. and Åström, B.T., "Experimental investigation of compression moulding of glass/PP–PP foam core sandwich components", *Journal of Thermoplastic Composite Materials*, 1999.

2. Breuer, U., Ostgathe, M. and Neitzel, M., "Manufacturing of all-thermoplastic sandwich systems by a one step forming technique", *Polymer Composites*, 1998, Vol. 19, No. 3, pp. 275–279.

3. Åström, B.T., Åkermo, M., Carlsson, A. and McGarva, L.D., "The all-thermoplastic sandwich concept", *Proceedings of the Forth International Conference on Sandwich Construction*, Engineering Materials Advisory Services, Warley, UK, 1998.

4. Åkermo, M. and Åström, B.T., "Modelling face–core bonding in sandwich manufacturing: Thermoplastic faces and rigid, closed-cell foam core", *Composites Part A*, 1998, Vol. 29A, No. 5-6, pp. 485–494.

5. McGarva, L.D. and Åström, B.T., "Experimental investigation of compression moulding of glass/PA12–PMI foam core sandwich components", *Composites Part A*, 1999.

6. Gibson, L.J. and Ashby, M.F., *Cellular Solids*, Pergamon Press, Oxford, UK, 1988.

7. McGarva, L.D. and Åström, B.T., "Insert integration in thermoplastic-based foam core sandwich components", *Journal of Sandwich Structures and Materials*, 1999.