Bending and bulging tests on steel sheet/aluminium foam sandwiches

H. von Hagen, W. Bleck
Aachen University of Technology, Department of Ferrous Metallurgy,
Intzestr. 1, D-52072 Aachen, Germany

Abstract

By combining thin steel sheets with an aluminium foam core a sandwich material is obtained. For structural applications, the bending and bulging properties of such sandwich material are extremely important, especially regarding failure mechanisms as well as point and line load concentrations. Therefore tests with roll-plated and resin bonded sandwich material consisting of different facesheet and foam core thicknesses have been performed to obtain data on the bending and bulging behaviour. The failure mechanisms under bending load are dependent on the relation of facesheet to core thicknesses resulting in core shear failure or indirect facesheet failure by line load concentrations. The first mechanism depends on the shear strength, the second on the compressive strength of the foam. The indentation behaviour in the bulging tests is mostly determined by the compressive strength of the foam. Therefore point and line concentrations and inhomogeneous load introduction have to be considered in sandwich construction. Thicker facesheets, a higher density of the aluminium foam core or a foam alloy with higher compressive strength may be used to minimize plastic deformation under point and line concentrations. To guarantee a weight optimization alloyed foams with high strength properties have to be favourized.

1 Introduction

Metallic foams are a very interesting material because of their unique combination of structural and functional properties. By combining thin steel sheets with an aluminium foam core a sandwich material is obtained. It combines a low overall density because of the lightweight core with an excellent bending stiffness evoked by the facesheets and functional properties of the foam core. For structural applications, the bending and bulging properties of these sandwich materials have to be known and the failure mechanisms have to be well-understood in order to avoid local plastic deformations or sudden failure of the construction.

2 Materials

Two different sandwich materials are tested, both consisting of steel facesheets/aluminium-clad steel facesheets (0,6 and 1,0 mm thick resp.) and an aluminium foam core. The first one is a roll-plated sandwich with a core of powdermetallurgical-processed foam by the Fraunhofer-route (alloys AlMgSi and AlSi12, foam density 0,22 to 0,48 g/cm³) [1,2]. The other sandwich material is based on melt-foamed aluminium Alporas (AlCaTi, foam density 0,2 to 0,42 g/cm³) bonded to the steel facesheets (DC04) or the Al-clad steel facesheets (similar to DC01, vacuum-killed) by means of an epoxy resin [2,3]. Varying foam core thicknesses (10 to 30 mm) are tested to gain information on the influence of the specimen geometry on the bending and bulging properties.

3 Testing methods

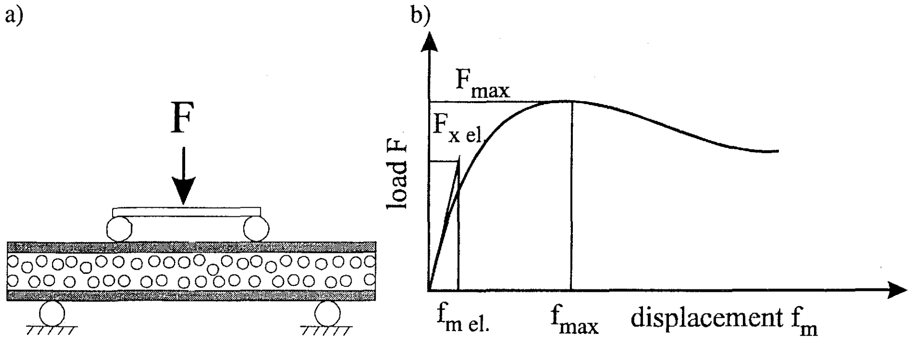

Fig. 1: Bending test, a) schematic test set-up, b) schematic load-displacement curve

Four-point-bending tests are carried out on the sandwich material according to the German standard DIN 53293 (similar to ASTM standard C 393), Fig. 1a. The load is introduced symmetrically with a constant rate of motion (1,5 mm/min) by two upper rolls (diameter 15 mm) with a distance of 120 mm; the distance of the bottom rolls is 240 mm. The sample size is usually 300x40 mm². Additional large samples with a core thickness of 15 mm (length 400 mm, bending length=distance of bottom rolls 320 mm) and 25 mm (length 600 mm, bending length=distance of bottom rolls 520 mm) were tested to determine the influence of the bending length. The results are determined by means of a load-displacement-curve as shown in Fig 1b that gives the middle deflection of the sandwich f_m and a load-deformation-curves indicating the deflection f_s at the load-introducing upper rolls. After a quasi linear-elastic start the curve shows plastic deformation and failure at a maximum load F_{max}. Afterwards the load decreases very slowly showing a rather high tolerance of the sandwich construction against total failure. The properties are determined according to German standard DIN 53293. The bending test gives information on the maximum bending moment, the bending stiffness (determined by the elastic load $F_{x\ el.}$ and the elastic deflections) and the stresses in the facesheets as well as the shear stress in the foam core during failure.

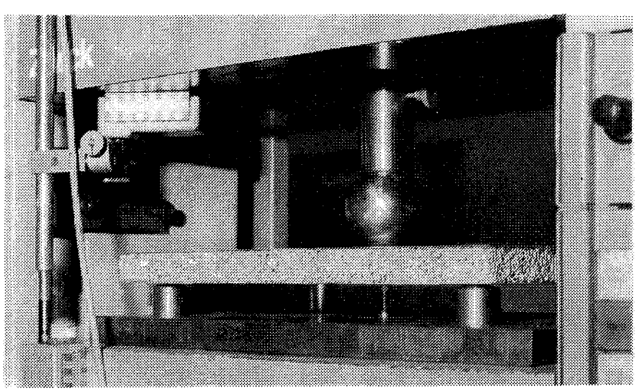

Fig. 2: Bulging test: test set-up with sandwich sample

The bulging tests are performed descaling and modifying the usual methods of testing large thin steel sheets. The samples are of the dimensions 300x200 mm², placed on four supporting sphere section points near the edges (240 to 150 mm). This set-up is shown as a view in Fig 2 and schematically in Fig 3a without a sandwich sample. The load is introduced into the center of the sample by a steel ball (diameter 55 mm) that is deforming the sandwich material. During the test the ball movement x and the displacement of the samples bottom side d up to a load of 2 kN are recorded, Fig. 3b.

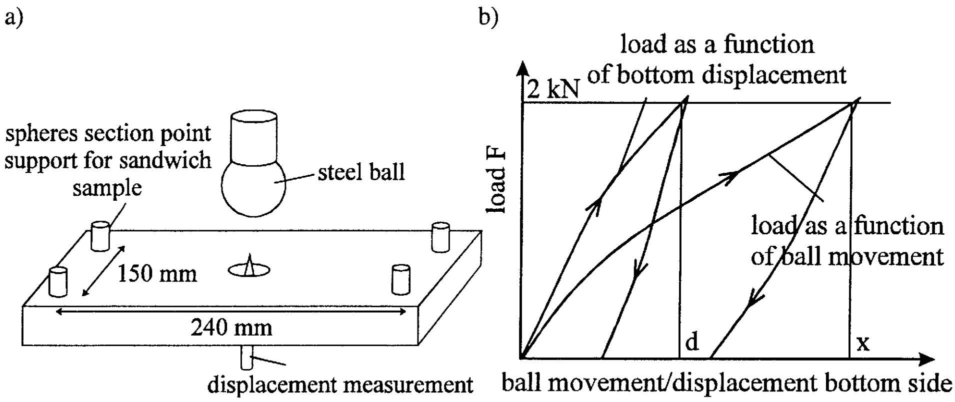

Fig. 3: Bulging test: a) test set-up without sample , b) schematic load-displacement curve

These load-displacement curves are similar to those of indentation tests with an cylindrical indenter [4]. By this arrangement the bulging displacement of the sandwich x and the plastic deformation d_{pl}=x-d of the foam core at a load of 2 kN can be determined, giving information on the bulging and indentation behaviour of sandwich material with different facesheet and foam core thicknesses as well as different aluminium foam alloys.

4 Results and discussion

4.1 Bending tests

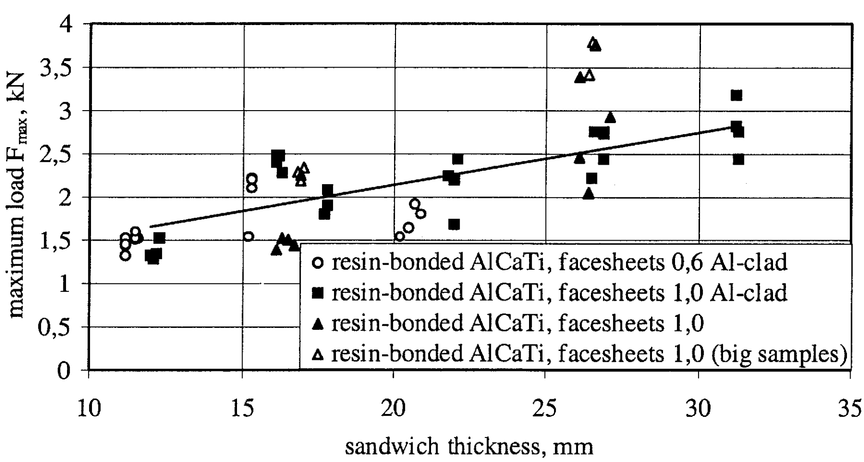

Fig. 4: Maximum load for different resin-bonded sandwiches with AlCaTi-foam core and different facesheets as a function of sandwich thickness (bending test)

An increase in maximum load can be observed with increasing sandwich thickness, as indicated by the full line for sandwiches with 1,0 mm thick Al-clad facesheets, Fig. 4. The low load values of sandwiches with 0,6 mm thick Al-clad facesheets and 20 mm foam core are based on the effect of line load concentrations that will be discussed later on. The material with 1,0 mm facesheets and 15 mm foam core also shows values distinctly below the line. In these cases the delamination occurs near the bonding zone below the theoretical loads associated with core shear failure.

Such a failure mechanism, well-known for sandwich constructions with delamination problems or butt-joints, only occured with the non-cladded material. This indicates the lower delamination strength of a bonding zone between the steel facesheet and the Al-foam for the used epoxy resin [5, 6]. The sandwiches with the same facesheets but 25 mm core thickness do not show any delamination problems and similar loads as the Al-clad material. In this case the failure is defined by the line load concentrations of the facesheets and not by core shear strength any longer. The large sandwich samples show higher maximum loads. This effect is based on the higher bending length. The samples undergo a mainly elastic deformation and therefore show plastic deformations and indentations at higher loads and displacements.

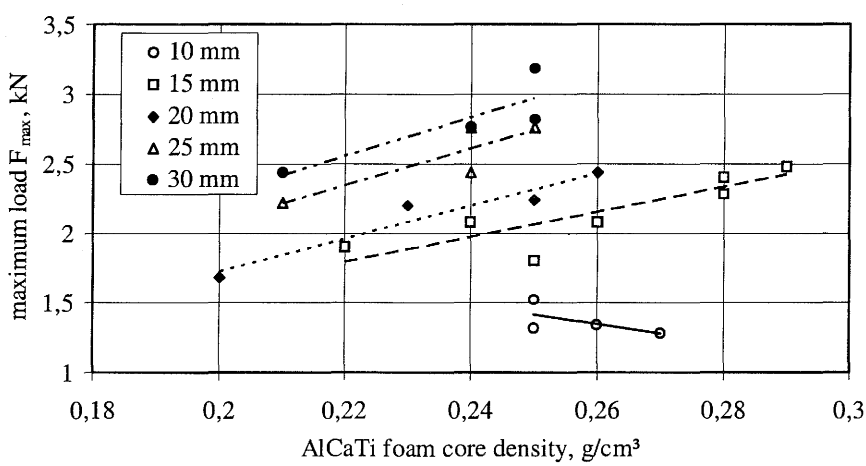

Fig. 5: Maximum load for resin-bonded sandwiches with different AlCaTi-foam core thicknesses as a function of foam core density (facesheets 1,0 mm thick, Al-clad)

Fig. 5 shows the influence of the foam core density on the maximum load of sandwiches with different AlCaTi foam core thicknesses. At 10 mm thickness the deformation of the sandwich in the bending test set-up is mostly elastic and the core density has no significant influence. This changes with growing foam core thickness. The compensation lines show an increase with rising foam core density and foam core thickness because of the growing necessary loads for plastic deformation. A similar influence has been shown for sandwiches made of glass fibre/resin bonded facesheets and polyvinylchloride foam cores in indentation tests [7]. Here higher core densities result in higher loads and failure of the facesheets by load concentrations. Lower maximum loads and a failure occuring before the densification of the foam core starts are recorded for sandwiches with thinner facesheets.

The tensile and compressive stresses induced in the facesheets by the bending process at the maximum loads (= during failure) are shown in Fig. 6. The yield strength of the materials have been determined to be 150 MPa for the 1,0 mm thick facesheets without cladding and around 300 MPa for both Al-clad materials. For the large samples according to the standard the stresses are only a bit lower than the yield strength indicating a good combination. Regarding the criteria for ideal combinations of facesheet and foam core thicknesses, there is a visible overmatching in most cases with a shorter bending length for 0,6 mm thick facesheets (dotted line) and especially for 1,0 mm thick facesheets (full line for Al-clad material). This effect is based on the influence of the shorter bending length, resulting in linear load cocentrations before failure by core shear or facesheet yielding. These results show that general assumptions for ideal combinations of facesheet and foam core as in [8] are only valid for the same limiting factors and have to be modified in real sandwich constructions including point and line load concentrations.

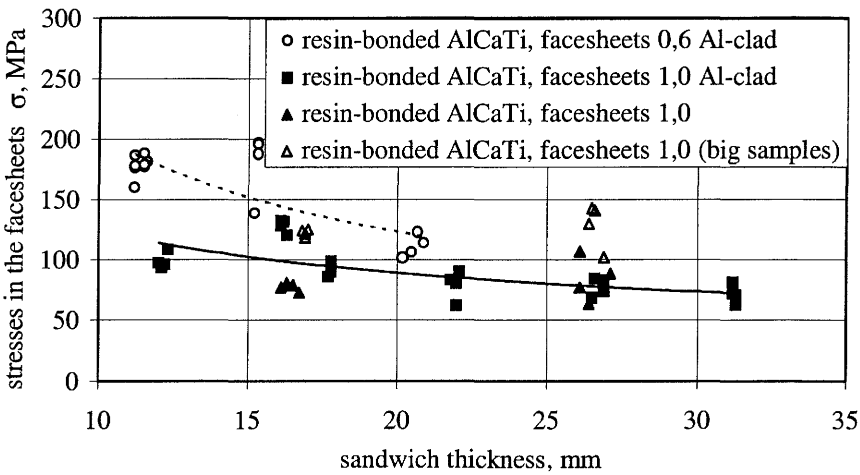

Fig. 6: Stresses in the facesheets at maximum load (= during failure) for resin-bonded sandwiches with AlCaTi-foam core as a function of sandwich thickness

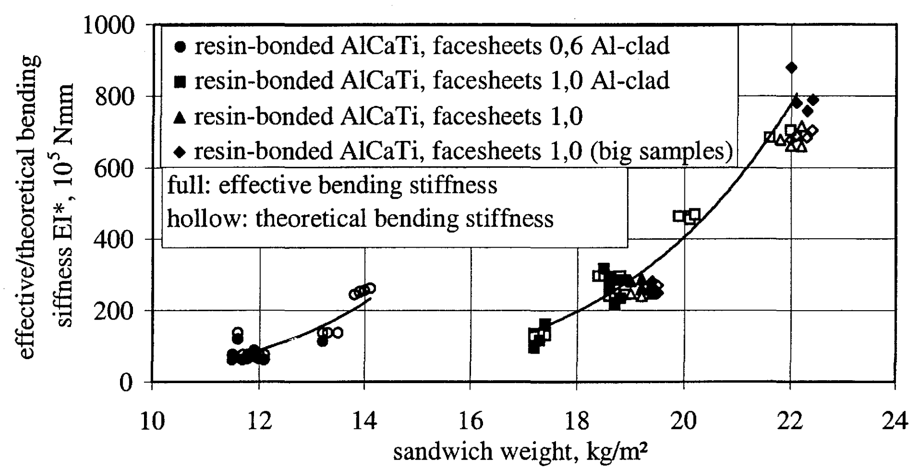

Fig. 7: Effective and theoretical bending stiffness per mm width for resin-bonded sandwiches with AlCaTi-foam core as a function of sandwich weight

A steel/aluminium foam sandwich construction shows an extreme increase of bending stiffness in comparison to compact materials [9]. The theoretical stiffnesses are verified by the results of the bending tests as shown for resin-bonded samples in Fig 7. The stiffnesses are only given with their theoretical values for some of the sandwich samples. In these cases the effective stiffness cannot be determined because the results for samples with thick foam cores are not valid. The samples show plastic deformation at early stages.

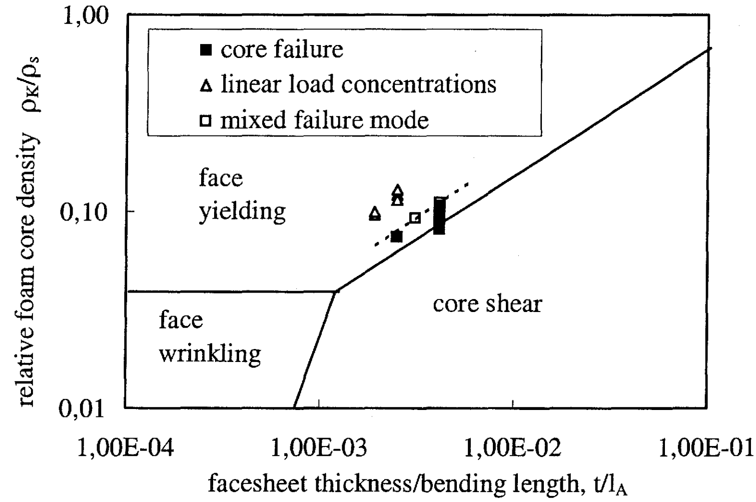

Fig. 8: Failure mode map for steel/Al-foam sandwich material using the failure mode areas of aluminium/polyurethane foam sandwiches (bending tests, foam core thickness 15 mm)

In Fig 8 the failure mode map for the steel/aluminium foam sandwich is shown using the failure mode areas of earlier works of Triantafillou and Gibson for aluminium/polyurethane foam sandwiches [10]. The areas of the failure modes have been transferred without changes. The core failure occured as a shear failure of the foam, the facesheet failure is an indirect failure by deformation based on linear load concentrations. A mixed failure mode is defined by a shear failure at one and a facesheet failure at the other load introducing roll. A failure by face wrinkling did not occur because the ratio of facesheet thickness to bending length was not low enough. The results show that the borderline between face failure and core failure is similar to that of aluminium/polyurethane foam sandwiches. The borderline can be assumed as a parallel line (dotted line in fig. 8). Regarding the small field of results more combinations of facesheet thickness and bending length have to be tested in the future.

4.2 Bulging tests

Fig. 9 shows the results of the bulging tests as the displacement of the sandwich bottom side. With the foam core thickness increasing and the stiffness arising the displacement of the sandwich bottom at 2 kN load decreases, shown as a degressive function for sandwich material with Al-clad facesheets of 1,0 mm thickness. Furthermore the use of thicker facesheets and alloyed aluminium foam as core material also lowers the displacement.

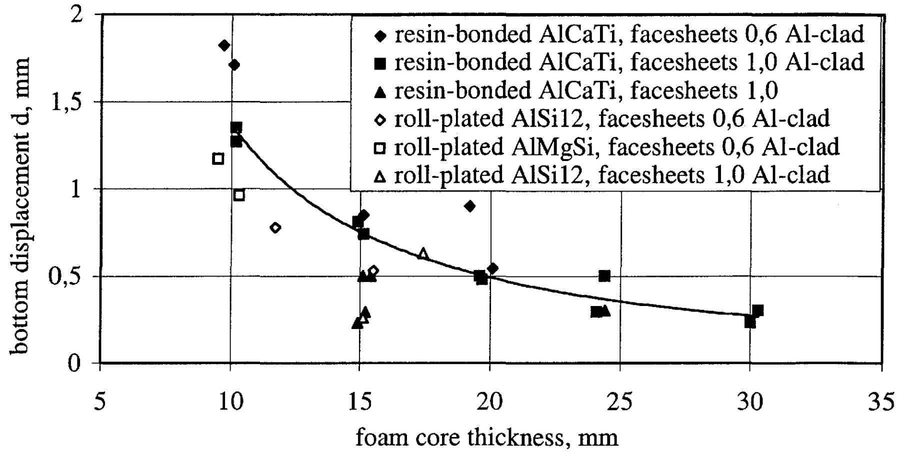

Fig. 9: Displacement at the sandwich bottom as a function of foam core thickness

The plastic deformation of the AlCaTi foam core of the same density is independent on the core thickness, Fig 10. This is shown this for the example of sandwiches with 1,0 mm thick Al-clad facesheets by the dotted line. Regarding both fig. 9 and 10 it becomes visible that the percentage of plastic deformation of the foam core as part of the total deformation increases with growing sandwich thickness. The sandwich construction becomes stiffer and higher point loads are introduced so that the bulging test becomes more and more an indentation test. The indentation behaviour is mostly determined by the compressive strength of the foam core and to a smaller extent by the facesheet thickness. A thicker facesheet distributes the introduced load more homogeneously. Therefore the indentation behaviour can be influenced by the facesheet thickness, the foam core density or the foam alloy to reduce the effect of point concentrations. The use of a high-strength alloy is combined with a weight minimization of the sandwich.

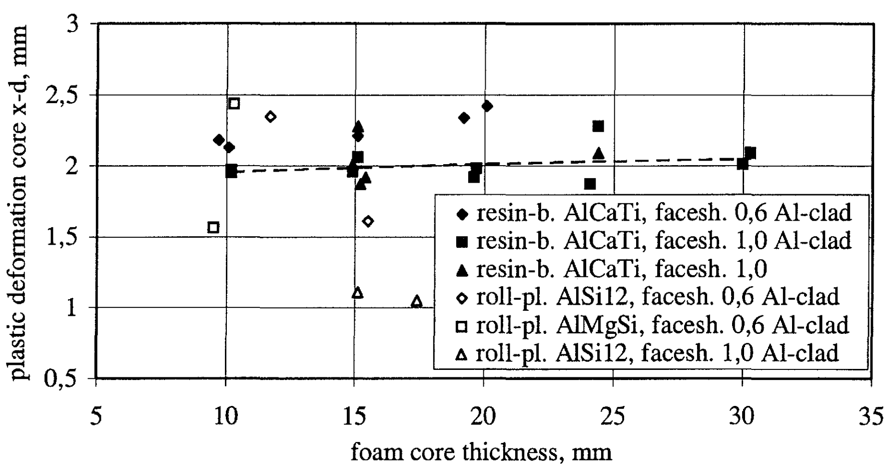

Fig. 10: Plastic deformation of the foam core as a function of the foam core thickness of resin-bonded (resin-b.) or roll-plated (roll-pl.) material with different facesheets (facesh.)

5 Conclusions

Usually the bending tests display no failure by buckling of the facesheets or by cracks in the bonding zone after a flawless production process. The high theoretical stiffnesses of steel/aluminium foam sandwiches are verified by the results of the bending tests. The failure mechanisms are dependent on the ratio of the facesheet and core thicknesses resp. bending length resulting in core shear failure or indirect facesheet failure by linear load concentrations. The first mechanism depends on the shear strength, the second mainly on the compressive strength of the foam. The indentation behaviour in the bulging tests is mostly determined by the compressive strength of the foam.

It is insufficient to determine an optimum sandwich design only on the base of ideal assumptions as homogeneously distributed loads and elastic properties like stiffness. Point and linear concentrations and inhomogeneous load introduction have to be considered in sandwich constructions. Neglecting the use of thicker facesheets because of their negative effect on the weight, this aim can only be achieved by using a higher aluminium foam core density or a foam alloy with higher compressive strength. A loss in weight advantage is combined with the first possibility. Therefore alloyed foams with high strength properties have to be favourized in order to reduce the effect of line and point concentrations.

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