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The Response of Sandwich Panels with Rigid Polyurethane Foam Cores under Flexural Loading

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ABSTRACT

An experimental study is undertaken to investigate and optimize the processing conditions in the fabrication of the sandwich structures designed for flexural load bearing applications. Sandwich beams with two glass/epoxy faces and a rigid polyurethane foam core were constructed under four different processing conditions. Wet and dry faces were applied at two temperatures to attain these four conditions. It has been shown that in comparison with the first processing condition (wet at 25°C) the specific flexural strength of the second one (dry at 25°C), third one (dry at 70°C) and fourth one (dry at 70°C with a thin layer of an adhesive) are increased 38%, 209% and 267%, respectively. The reason behind this significant enhancement is demonstrated to be related to the debond strength of the core-face interface. It has been demonstrated that the debond strength of the core-face and core plays an important role in enhancing the flexural rigidity and controlling of the failure mechanisms. If the core material be polymeric foam, the core and debonding strengths at the core-face interface will almost entirely dictate the structural sandwich composite performance especially under flexture. Results showed that the core strength decreases, but the debonding strength of the core-face interface increases with the increment of the processing temperature during the preparation of the rigid polyurethane foam core. We also observed that with increasing the debonding strength of the core-face interface, the failure mode changes from debonding of the core-face interface to the failure of the face. Finally, the sandwich structures were obtained with the excellent performance under flexural loading.

Key Words:
polyurethane foam;
sandwich structure;
flexural;
debonding strength;
failure mode.

INTRODUCTION

Sandwich construction is widely used because of its ability to provide high bending stiffness coupled with light weight. The use of composite sandwich structures has significantly increased particularly in marine and aviation applications in recent years [1-3]. Sandwich structures are being increasingly used in the primary structures such as vertical tails, horizontal flaps, and boat hulls, now. Their good shock resistance combined with high flexural rigidity, furthermore makes them ideal for the

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manufacture of large panels and ship hulls [4].

Durability is one of the key design parameters for any structure where its safe life must be guaranteed before the initiation of observable damage. The sandwich structures are mostly subjected to flexural loading when they are used in ship hulls [4-7].

Since sandwich structures are manufactured by different manufacturing methods such as resin transfer moulding (RTM), compression moulding, and autoclave vacuum bag moulding, two important factors are frequently overlooked. First, the bonding between the face and core of sandwich structures is assumed to be perfect bonding. The conventional manufacturing method of sandwich structures is completed by adhesive joining of cores to the separately prepared composite faces. The joining process during sandwich fabrication is a complicated process which requires strict quality control. A number of investigators have noted that sandwich structures can fail in a number of different modes. The failure modes of the sandwich beams, which are categorized as the failure of the face by fibre breakage, failure of the core or delamination of the core/face interface by shear and failure of the core in compression [8] or combination of them, are closely related to the adhesion characteristics between the face and core of the sandwich structures. Second, in many cases the manufacturing parameters of the sandwich structures are selected as the same as those of the composite faces [9]. A potentially useful tool for design of sandwich structures is the concept of a failure mode map, where the failure modes are identified as a function of the design variables such as face and core and structure dimensions, and the core and face material properties [8].

Over the years, many researchers have studied sandwich structures with special emphasis on the face sheets and it is generally agreed that the behaviour of face sheet materials is well known and therefore could be included in the design process. However, it cannot be said the same about the sandwich structures materials, especially those made of foam cores. In addition, it has been demonstrated that during flexural loading in static or cyclic, the core section basically controls the failure of the sandwich structures [10-15].

The effect of processing conditions on mechanical response of sandwich structures has not been well understood. In the present investigation, the effect of different processing conditions on the flexural properties and the failure modes of foam core sandwich structures were studied.

EXPERIMENTAL

Materials

The sandwich core material was commercial grade rigid polyurethane foam. Both components of this foam were supplied by Bayer under the trade name of 610W. The sandwich beam facing were fabricated by using an epoxy resin (Araldit LY5052 with HY5052 hardener) which supplied by Hunstman Europe. They were reinforced with a commercial grade E-glass woven plain weave fabric of 200 g/m^2 surface density.

Sandwich Panels Fabrication

The manufacturing of the sandwich panels was carried out in two steps: (i) the fabrication of composite faces by manual laying up of two layers of woven glass fibre separately on the female and male mould surfaces (the nominal face thickness was 2.8 mm and fibre content and density of the composite faces were 50±2 % wt and 1.63 g/cm^3 respectively), (ii) The two components raw materials of the polyurethane foam were mixed together for 60 s with an overhead stirrer. The mixture was injected into a rectangular closed steel mould. Sandwich panels of 10×200×300 mm were prepared by using this steel mould at 25 or 70^{o}C. The effects of processing temperature and gel time of epoxy resin were investigated by selecting different processing conditions that are given in Table 1. Tensile modulus of the epoxy/glass fibre faces and 610W polyurethane foam can be compared by taking into account 40 GPa and 0.5 GPa, respectively.

Mechanical Tests

Three-point flexural tests were conducted on the cores and sandwich beams according to ASTM C393-94 standard [16] as shown in Figure 1. The three-point flexural fixture was installed in a hydraulic testing machine (MTS). Flexural tests on sandwich structures and foam core specimens were conducted at room temperature in displacement control at a crosshead speed of 1 mm/min and 5 mm/min, respectively.

The density of foam cores was measured according

Table 1. Processing conditions used for the construction of sandwich structures.

Sample	Processing conditions	Curing time and temperature
1	Complete wet face	10 days at 25°C
2	Completely cured and dried face	10 days at 25°C
3	Completely cured and dried face (70°C)	2 h at 70°C and 7 days at 25°C
4	Completely cured and dried face (70°C); (A thin layer of epoxy resin (30 μm) applied on the face)	2 h at 70°C and 7 days at 25°C

to ASTM C271 standard [17]. The results that reported here are the average of at least five measurments.

RESULTS AND DISCUSSION

Response of Sandwich Composites

Flexural test results of the sandwich panels that were prepared in different processing conditions are presented in Table 2. In the preparation of the faces of sample 1 the applied epoxy resin was in the gelation step (i.e., the faces were perfectly wet) while, the epoxy resin of the face of sample 2 has been perfectly cured and dried before injection of the foam core material into the mould cavity. Results show that the flexural properties of sample 2 are significantly better than sample 1.

Samples 3 and 4 were prepared at 70°C. When the foam was injected into the mould, the faces of samples 3 and 4 had been completely cured and dried and their temperature was 70°C. A thin layer of the epoxy resin (30μm) was applied on the surface of sample 4 by a film applicator. Flexural properties of samples 3 and 4 are higher than those of samples 1 and 2 (Table 2). For example, the specific flexural modulus and flexural strength of sample 4 are higher than those of sample 1 by 55% and 65%, respectively. Therefore, we concluded that applying a thin layer of resin not only increases the stiffness of the sandwich structure but also increases the bending strength of the foam core sandwich structure.

The load deflection curve of a specimen as a representative of each condition is depicted in Figure 2. This figure shows that the processing condition has a significant effect on the mechanical properties of all sandwich structures. Figure 2 and the data represented in Table 2 show that the processing condition has no effect on the elastic response of sandwich panels at small deflection (i.e., deflection lower than 0.5 mm), but it has a significant effect on the load bearing and the toughness of these structures (deflection higher than 2.2 mm). The flexural behaviours of the samples that

Table 2. Experimental data of sandwich panels (standard deviations in brackets).

Sandwich structure	Processing conditions	Flexural strength, σ_f (MPa)	Specific flexural strength σ_f/ρ_f (m)	Flexural modulus, E_f (MPa)	Specific flexural modulus E_f/ρ_f (km)	Core density, ρ_f (kg/m^3)
1	Wet face (25°C)	3.8 (0.3)	2100	283 (83)	157	180
2	Dry face (25°C)	5 (2.5)	2900	307 (80)	178	172
3	Dry face (70°C)	9.3 (1.5)	6500	309 (33)	218	142
4	Dry face + 30 μm resin (70°C)	11 (2)	7700	386 (100)	272	142

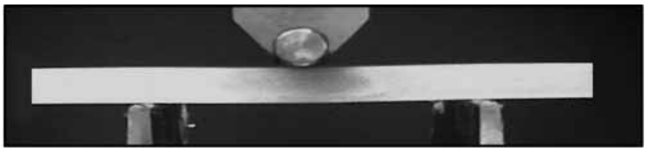

Figure 1. Sandwich beam loaded in flexural.

have been fabricated in four different conditions and illustrated in Table 1 are well matched with the results reported in the literatures [18, 19].

Since the foam core density affect significantly the response of a sandwich panel [8], we tried to prepare the above mentioned sandwich panels with similar foam core density. But, it is not possible practically to achieve to this goal regarding the temperature variations and tools limitations. Therefore, the specific flexural properties that reported in Table 2 belong to the samples with various core densities. Table 2 shows that the specific flexural strength of the prepared sandwich structures in the 2nd, 3rd and 4th processing conditions increased by 38%, 209% and 267%, respectively as compared with the 1st processing condition. It is interesting to mention that these four processing conditions are being used in the industry and the manufacturers may not be aware that these conditions have so significant effect on the flexural properties of these structures.

What is the reason behind this significant enhancement? The question is very simple but the answer is very complicated. One may say that it might be due to the strengthening of the core material that is thermoset polyurethane foam produced from reaction of polymeric isocyanate (part A) and polyol (part B). We also know

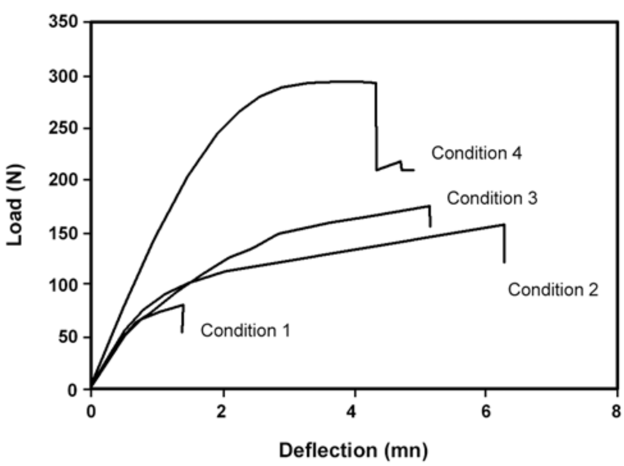

Figure 2. Load-deflection curves of the sandwich panels at four different processing conditions.

that the core plays an important role in enhancing the flexural rigidity [10]. To explore this point and also for investigation of the temperature effect on the flexural properties of foam core material, foam samples have been manufactured at 50, 70 and 100°C by using the same steel mould. Flexural properties of these samples are presented in Table 3. Results show that by increasing the processing temperature, the flexural strength and modulus of this rigid polyurethane foams not only do not increase but decrease. In order to eliminate the variation of unavoidable foam densities, the specific flexural strength has been calculated and reported in Table 3. The specific flexural strength of the prepared foam at 50°C is about 3% higher than the one prepared at 70°C and about 44% higher than the one prepared at100°C.

Load-deflection behaviours of a sample as a representative of three fabricated foams are shown in Figure 3. It can be seen that the failure load of sample 1 is 1% higher than that of sample 2 and 40% higher than that of sample 3. These results also show that the effect of the temperature variations from 50 to 70°C on the foams strength is negligible. It is noticeable that when the processing temperature rises from 70 to 100°C, the strength of rigid polyurethane foams increase approxi-

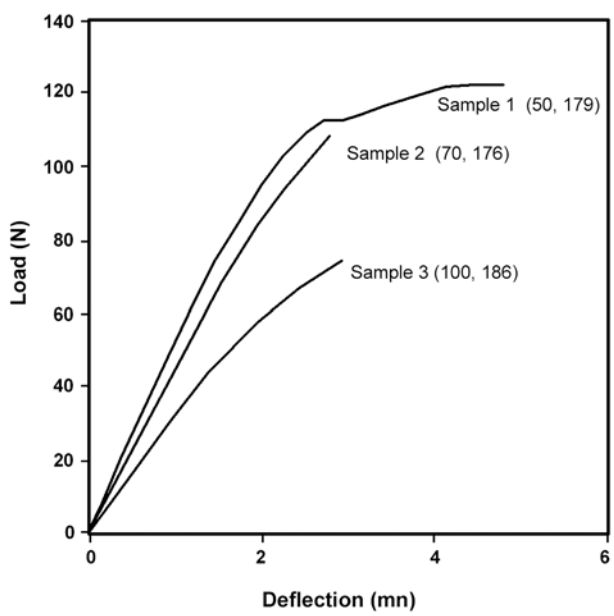

Figure 3. Load-deflection curves of core materials (the right hand side number in the parentheses is the foam core density (Kg/m$^{3)}$ and the left hand side number is the processing temperature in centigrade).

Table 3. Experimental data of foam cores (standard deviations in brackets).

Sample	Foam density, ρ_f (Kg/m^3)	Processing temperature (°C)	Flexural strength, σ_f (MPa)	Specific flexural strength σ_f/ρ_f (m)	Flexural modulus (MPa)
1	176 (4)	50	5.2 (0.2)	2950	153 (6)
2	179 (9)	70	5.1 (0.5)	2850	136 (17)
3	186 (14)	100	3.8 (1.0)	2043	100 (20)

mately up to 36%. Initial linear portion of three curves is due to linear elastic deformation of the cell structures. As the cell begins to rupture due to stretching, the slope of the load-deflection curve changes and the foam almost uncontrollably deforms and finally fail at maximum load.

It is well known that the strength of closed cell foam derives from its edges, walls, faces and the entrapped gas [10]. In particular, two phenomena will dominate the foam failure during flexural. One of them is cell stretching in the tension side of the specimen, which initiates multiple cracks at the edge of specimen just blow the central loading point, and the other is coalesce into a dominant crack causing the eventual failure of the foam. Failure mode of the foam cores alone is shown in Figure 4. It is appeared that the stretching phenomenon is the dominant failure mode and speeded by increasing the processing temperature of the rigid polyurethane foams especially at higher temperatures than 70^{o}C.

The above discussion reveals that the significant increase of flexural properties of sandwich panels that prepared in different processing conditions is not related to the strengthening of foam core. It was necessary, therefore, to investigate further the failure mode of these sandwich panels.

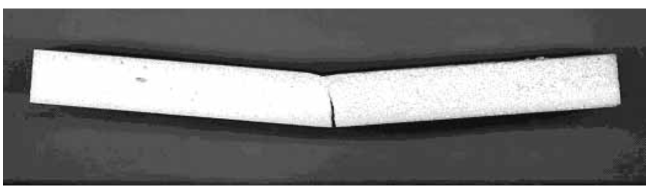

Figure 4. Failure mode of foam core alone.

Failure Mechanism of Sandwich Structures

Failure mode of sample 1 is shown in Figure 5. Core-face interface debonding is the principle failure mode for this sample. Debonding exactly initiated near the loading point at the core-face interface and rapidly propagated towards the edges of specimen along the interface. This kind of failure is reported elsewhere [10] and it is a dominated failure mode in thin face sandwich structures. Figure 6 shows debonded face of sample 1. It is observed that debonding of the core-face exactly occurs at the core-face interface without any trace of foam on the debonded face.

The failure mode of sample 2 was similar to sample 1, but the debonding speed for the former is slower than the latter one. The failure mode of sample 3 is the same as the failure mode of samples 1 and 2, but with three differences. First, for sample 3 the debonding of the core-face only initiates from one side of the loading point. Second, the debonding speed of sample 3 is very slower than that of sample 1. Third, significant amount of the foam remains on the debonded face of sample 3,

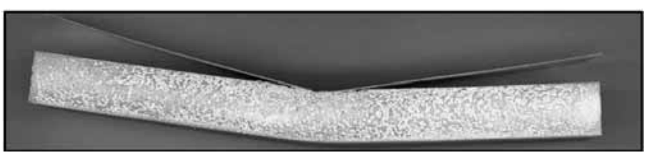

Figure 5. Failure mode of sandwich panel, sample 1.

Figure 6. Debonded face of sample 1.

Figure 7. Debonded face of sample 3.

as shown in Figure 7. This indicates that there is a good bonding between the core and face, and debonding initiates at the sub-interface instead the core-face interface as it is reported elsewhere [8, 20].

The failure mode of sample 4 that has been shown in Figure 8 was face failure in loading point, i.e., the bonding strength of the core -face is very higher than the face strength.

As it was mentioned, sample 2 offers better flexural properties than sample 1. This phenomenon can be related to the higher bonding strength of the core-face in sample 2. This is due to the slower growth rate of the debonding core-face of this sample in comparison with sample 1. It is interesting to note that there is not remain any polyurethane material on the debonded faces of sample 1; while there was a trace of urethane foam on the debonded faces of sample 2. This implies that bonding strength core-face has increased. Also, the failure mode of sample 3 was the debonding of the core-face, but the core-face bonding strength of sample 4 is rather high. Thus, the face failure occurs instead of the debonding of the core-face.

Therefore, increasing the flexural properties (for example 267% increasing in the specific flexural of 4th processing condition samples compared with the 1st processing condition) of these sandwich structures can be related to the core-face bonding strength that increases with the increasing of the curing temperature and applying a thin layer of epoxy resin. Thin layer of resin acts as an adhesive film. That is common in making sandwich structures. In this case, the raw material of polyurethane foam in the mould exist as a liquid form. Increasing the mould temperature during curing causes the viscosity of the liquid foam decreases. It followed by the diffusion of polyurethane chains into the epoxy resin chains in the face.

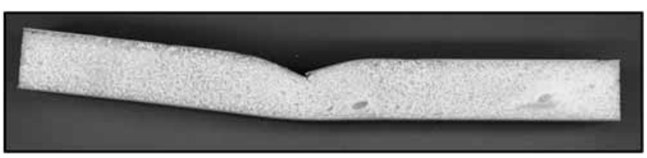

Figure 8. Failure mode of sandwich panel, sample 4.

Adams et al. [21] showed that at least by two mechanisms the core-face bonding strength increases, namely diffusion of polyurethane chains into the matrix of sandwich faces and electrostatic or van der Waals forces. By the second mechanism, the reaction takes place between reactive functional groups of isocyanides and epoxy resin [22]. In sample 4, there is two liquids in contact with each other (the liquid foam and the thin layer of epoxy resin). Therefore, both physical and chemical interactions occur and consequently the core-face bonding strength increases [7, 11, 20]. By the way, The strength of interface, controls the failure mechanisms and increaces the flexural properties of sandwich panels nearly three folds.

CONCLUSION

Three-point flexural tests were carried out on sandwich beams with glass/epoxy faces and the rigid polyurethane foam core manufactured by four different processing conditions. Results showed that the flexural properties of the sandwich structure with completely cured and dried faces were better than that of the wet faces. The flexural properties of the sandwich structure with a thin layer of the resin on the dry faces were even much better than that of the dry faces alone and the specific flexural strength of this sandwich structure increased by 267%.

We demonstrated that the debonding strength at the core-face interface is increased with increasing of the curing temperature and consequently, the flexural properties of the sandwich structure improveds.

Both strength and flexural properties of the rigid polyurethane foam alone reduce by increasing of the processing temperature from 25 to 70^{o}C. In the other word, in the fabrication of sandwich structures it is necessary to have suitable core and debonding strengths at the core-face interface. So we concluded that the optimum curing temperature is about 70°C for this foam core sandwich panel.

It is shown that, when the sandwich structure's core-face bonding strength is low, the failure mode will be debonding of the core-face interface. But for a high core-face bonding strength the failure mode will be the glass/epoxy faces failure. Results show that the strength of interface controls the failure mechanisms and affects the flexural properties of sandwich panels nearly three folds.

REFERENCES

1. Composites Fabricators Association (CFA), *Historic Growth and Forecasts;* Available at www.cfa-hq.org, (2002).
2. van Erp G., Cattell C., Heldet T., Fibre composite structures in australia's civil engineering market: An anatomy of innovation, *Prog. Struct. Eng. Mat.*, **7**, 150-160 (2005).
3. Scudamore R.J., Cantwell W.J., The effect of moisture and loading rate on the interfacial fracture properties of sandwich structures, *Polym. Comp.*, **23**, 406-417 (2002)
4. Dai J., Thomas H., Flexural behaviour of sandwich beams fabricated by vacuum-assisted resin transfer moulding, *Comp. Struc.*, **61**, 247-253 (2003).
5. Yoshii A., Optimum design of advanced sandwich composite using foam core, *Adv. Comp. Mat.*, **2**, 289-305 (1992).
6. Thomsen O.T., Theoretical and experimental investigation of local load bending effects in sandwich plates, *Comp. Struc.*, **30**, 85-101 (1995).
7. Zenkert D., Hallstron S., Shipsha A., *Design Aspects of Marine Structures*, Maryland University, 28-32 (1999).
8. Jongman K., Stephen R., Design of sandwich structures for concentrated loading, *Comp. Struc.*, **59**, 365-373 (2001).
9. Lee C.S., Lee D.G., Co-cure method for foam core sandwich composite manufacture, *Comp. Struc.*, **66**, 231-238 (2004)
10. Mahfuz H., Islam M.S., Rangari V.K., Response of sandwich composites with nanophased cores under flexural loading, *Compsites: Part B*, **35**, 543-550 (2004).
11. Kulkarni N., Mahfuz H., Jeelani S., Carlsson L., Fatigue crack growth and life prediction of foam core sandwich composite under flexural loading, *Comp. Struc.*, **59**, 499-505 (2003).
12. Carlsson L., Sendlein S., Merry S., Characterization of core/face shear fracture of composite sandwich beam, *J. Comp. Mater.*, **25**, 101-116 (1991)
13. Kanny K., Mahfuz H., Thomas T., Dynamic mechanic analysis and flextural fatigue of PVC foams, *Comp. Struc.*, **58**, 175-183 (2002).
14. Kulkarni N., Mahfuz H., Jeelani S., Fatigue failure mechanism and crack growth in foam core sandwich composite under flexural loading, *J. Reinf. Comp.*, **23**, 83-92 (2004).
15. Marshal A.C., Sandwich Construction, *In: Handbook of Composites*, Lubin G. (Ed.), Van Nostrand Reinhold, New York, 557-601 (1982).
16. ASTM C 393-94, Test Method for Flexural Properties of Flat Sandwich Constructions, *Annual Book of ASTM Standards*, Vol.15, part 3, 21-24.
17. ASTM C271-94, Test Method for Density of Core Materials for Structural Sandwich Constructions, Annual Book of ASTM Standards, Vol. 15, part 3, 1-4
18. Corigliano A., Rizzi E., Papa E., Experimental characterization and numerical simulations of a syntactic-foam/glass-fibre composite sandwich, *Comp. Sci. Tech.*, **60**, 2169-2180 (2000).
19. Mine R.A.W., Alis A., Numerical simulation of the progressive collapse of polymer composite sandwich beams under static loading, *Composites: Part A*, **33**, 11-26 (2002).
20. Borsellion C., Calabrese L., Valenza A., Experimental and numerical evaluation of composites and composite structures, *Comp. Sci. Tech.*, **64**, 1709-1715 (2004).
21. Adams R.D., Comyn J., Wake W.C., *Structural Adhesive Joints in Engineering*, Chapman and Hall, London, 167-172 (1997).
22. Deepak S., Babu J., Prasun M., Mahfuz H., Effect of processing conditions and properties on the debond fracture toughness of foam-core sandwich composite, *Composite: Part A*, **34**, 1085-1095 (2003).